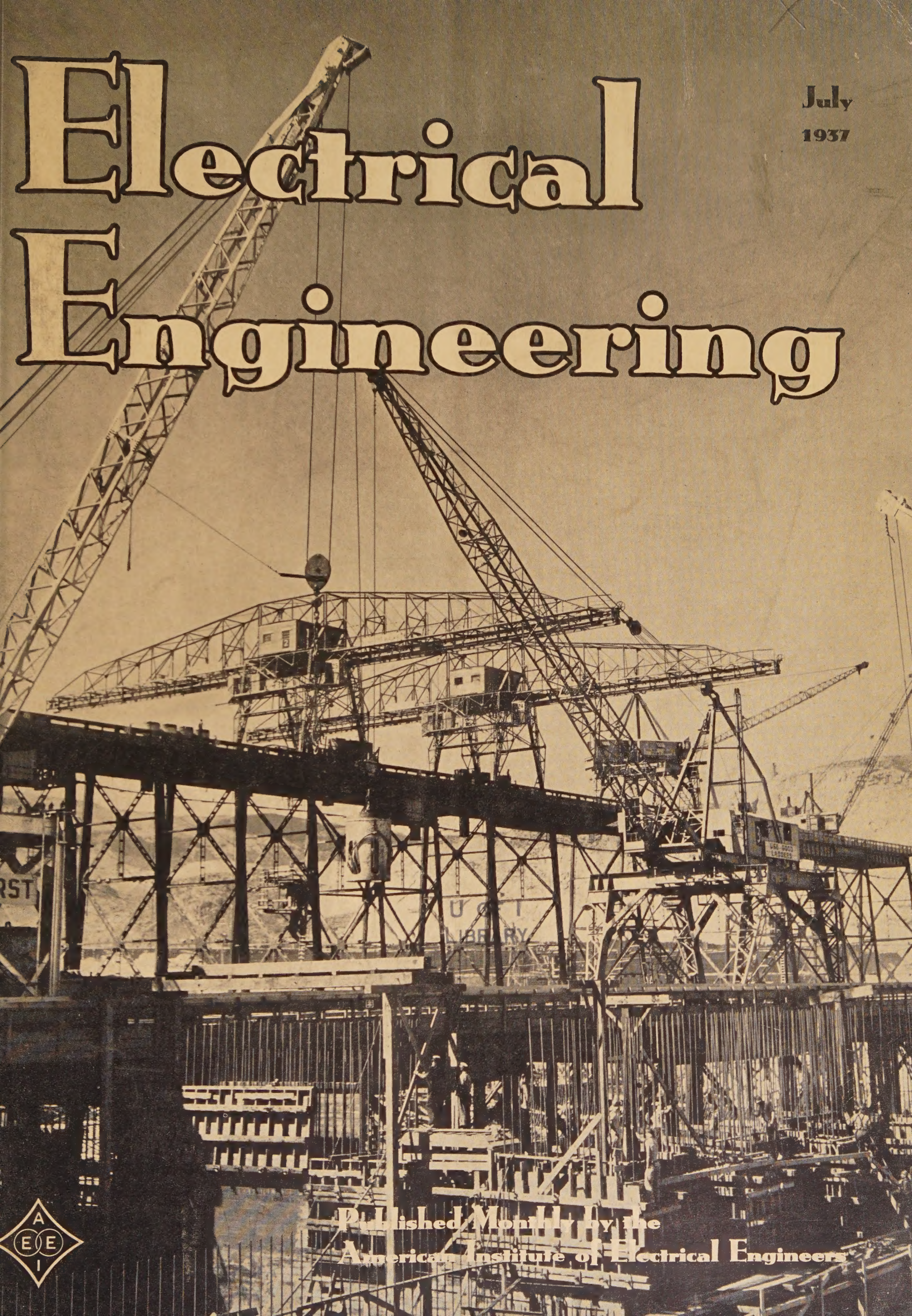
Electrical Engineering

July
1937



Published Monthly by the
American Institute of Electrical Engineers

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Electrical Engineering

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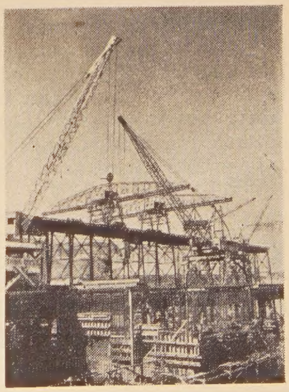
The Cover

Construction view of Coulee Dam, feature item of the inspection trip program of the AIEE 1937 Pacific Coast convention (see news section)



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High Lights

Pacific Coast Convention. An all-day inspection trip to the Grand Coulee project on the Columbia River is one feature that has been included on the program of the Institute's 1937 Pacific Coast convention to be held in Spokane, Wash., August 30–September 3, in the heart of the Pacific Northwest. Other attractions include a high-class technical program, a joint session with the Institute of Radio Engineers, the usual sports competitions, and special entertainment (*pages 910–12*).

Huge Telescope Being Welded. Framework for the 200-inch telescope now being built in a new observatory on Mt. Palomar, Calif., will consist of electric-arc-welded units bolted together at the site. Astronomers estimate that this new instrument will penetrate the universe to a distance of a billion light-years (*pages 783–6*).

Charles Le Geyt Fortescue. An appreciation of this noted electric-power-transmission engineer (who died December 4, 1936), prepared by one who was associated with him for many years, outlines his many contributions to the electrical industry (*pages 781–3*).

Electrical Computer. A search for a simple computing device to simplify and expedite the calculations involved in the design of the overhead catenary for an extensive railroad electrification led to the development of an electrical computer, the circuit of which represents an exact analogy of the mechanical system embodied in the messenger cable of a catenary span (*pages 787–90*).

Summer Convention. As this issue goes to press, the Institute's 1937 summer convention is being held in Milwaukee, Wis. At the opening session, election of 2 noted engineers as AIEE Honorary Members was announced, and new officers to serve the Institute during the ensuing year were named (*pages 913–14*).

Letters to the Editor. Readers of Electrical Engineering continue to express themselves informally on a variety of subjects through the "Letters To The Editor" columns (*pages 917–18*).

Saturated Synchronous Machines. Effects of saturation in salient-pole and cylindrical-rotor synchronous machines operating under steady load may be analyzed by a method based upon the 2-reaction theory, with good agreement between calculated and test results; torque angle is obtained by using saturated quadrature synchronous reactance rather than unsaturated reactance (*pages 858–63*).

Ignitors. A rod of high-resistivity material is used in ignitron tubes to initiate the discharge by the formation of an arc between the rod and the mercury-pool cathode in which the rod is immersed. Current required by the ignitor should be as small as possible; shaping the rod to a point and slotting it greatly increase its effectiveness (*pages 810–12*).

Distance Relays. Distance-measuring and directional elements are used in various relay combinations to provide fault protection in power systems; the performance of distance relays may be determined from the effective impedance presented to the element, which may be expressed in terms of certain fundamental quantities and thus reduce to a minimum the labor involved in the calculations for any specific situation (*pages 833–44*).

Photoelectric Hysteresigraph. Initial magnetization curves or any desired symmetrical or unsymmetrical hysteresis loops may be recorded graphically on the fluorescent screen of a d-c instrument which depends for its operation on a photoelectric fluxmeter (*pages 805–09*).

Directors' Report. The annual report to the membership of the Institute's board of directors summarizes activities and the work of national committees during the year. Membership statistics and financial statements are included (*pages 791–804*).

Potier Reactance. Calculation of Potier reactance, which is a combination of reactance, change of saturation, and change of flux form, is possible by means of 3 approximate empirical methods given in this issue. The probable accuracy of the methods for typical machines is shown (*pages 813–18*).

Oil-Impregnated Paper. Extended tests indicate that there is no correlation between dielectric loss and electrical life of oil-impregnated paper insulation, and that gas-free specimens are superior to any specimens saturated with gas at pressures up to 200 pounds per square inch (*pages 845–9*).

Relay Operation. When synchronous machines hunt or fall out of step with one another an oscillating interchange of power may cause relays to operate unnecessarily. Some remedies for such incorrect relay operation have been suggested (*pages 823–32*).

The Perfect Reading Page. Is Electrical Engineering's "easy reading" page really easier to read? This question is answered in part by a writer thoroughly qualified to draw conclusions on the subject (*pages 779–81*).

Distortion of Traveling Waves. The shape of a lightning wave traveling on a transmission line is altered by corona at normal operating frequency. How to predict the distortion is described in a paper in this issue (*pages 850–6*).

Lightning Arresters. A new station type of autovalve lightning arrester is described in a paper in this issue (*pages 819–22*).

DISCUSSIONS

Appearing in this issue are discussions of the following papers:

Communication

Electric Welding

Electrical Machinery

Electronics

Instruments and Measurements

Power Transmission and Distribution

Statements and opinions given in articles and papers appearing in Electrical Engineering are the expressions of contributors, for which the Institute assumes no responsibility. Correspondence is invited on all controversial matters. ¶ Subscriptions—$12 per year to United States, Mexico, Cuba, Porto Rico, Hawaii, Philippine Islands, Central and South America, Haiti, Spain, Spanish Colonies; $13 to Canada; $14 elsewhere. Single copy $1.50. ¶ Address changes must be received by the fifteenth of the month to be effective with the succeeding issue. Copies undelivered because of incorrect address cannot be replaced without charge. ¶ Electrical Engineering is indexed annually by the Institute, weekly and monthly by *Engineering Index*, and monthly by *Industrial Arts Index*; abstracted monthly by *Science Abstracts* (London).

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Electrical Engineering

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Branch Activity—*A Message From the President*

ON August 1, 1936, there was no phase of the Institute work of which I knew so little as I did about the work of the Student Branches. Today there is no phase in which I am more interested, or which I feel is better conducted. A successful Branch must overcome some natural handicaps. If limited to the 2 upper classes, the membership must be completely replaced every 2 years. There are many claims on the students' time. The potential members have had little experience in organization affairs. Active membership is of such short duration that there is little opportunity for the development of leaders. In a Section the average chairman comes to office with several years' experience in Section and committee work, but the Branch chairman seldom has more than one year's training in Branch activity. In the Sections, past-chairmen are a source of inspiration, counsel, and guidance, while in the Branches, the past-chairmen are lost through graduation.

Why, then, is the Branch movement so successful? From my observation, it is because of 3 factors: the enthusiasm of youth; the desire to make use of every agency in acquiring an engineering training; the advice and guidance from the counselors.

From my visits to Branches and Branch conventions come several ideas as to how Branch activity is being successfully carried on. I believe that these ideas are worthy of record, and hope that the future will see many additions to the record. The Student Branch should be organized on the following fundamental principles.

It is an honor and a duty to be a member; a privilege to attend the meetings. The officers should be selected from the most capable and distinguished members, for certainly capable, enthusiastic officers are essential for a successful Branch. The meetings must be worth while. At the close of the meeting, each one attending must feel that he has gained professionally by being present. Discussion of the subject presented should be stimulated and encouraged, for often it is the most valuable part of the meeting. It should be understood that the meetings are closed to nonmembers, excepting on specific invitation. The Branch officers should be responsible for, and carry on, the Branch activities, depending upon the counselor only for advice and guidance.

The program should be planned in advance and as a co-ordinated whole, for it is the most important of the Branch activities. Although programs should be broadened beyond the highly theoretical and basically technical, the Branch should always remember that it is an integral part of a national technical society. A meeting where engineering results are demonstrated with the aid of equipment is extremely interesting and very popular. Speakers should be sought from 3 sources: graduate engineers in industry; faculty members from the home and other colleges; and from the membership of the Branch. Exchange of faculty speakers between neighboring Branches produces good results.

The year may be divided into 2 periods, providing 4 periods within a cycle of membership. Officers would then be elected twice each year, resulting in more opportunities for service and less time required from each officer. Rotation in office, with its advantages, is then possible. In one school where such a plan is followed, an observer from each of the freshman and sophomore classes is invited to attend the executive committee meetings, as well as the Branch meetings. These observers do not pay dues, are carefully selected by the Branch, and the selection is considered an honor. In this school, regular membership is open only to juniors and seniors. As each sophomore class becomes junior, there are 4 men who know something of the purposes, conduct, and activities of the Branch, and these men almost invariably join and take an active part in the Branch affairs.

Where several Branches are geographically close, joint activities are inspiring to each. During the last year, I saw 2 illustrations of the effectiveness of such a plan: at Pittsburgh in a joint afternoon session of the Branches from Carnegie Institute of Technology, the University of Pittsburgh, and the University of West Virginia; in North Carolina between Duke University, the University of North Carolina, and the North Carolina State College. Such joint activities provide training in co-operation, and offer the stimulation of competition.

Co-operation from a neighboring Section is of great assistance. Although the primary responsibility rests on the Section, the Branch should be very receptive. Many Sections offer a reduced price to Branch members if they attend a Section dinner. In the West, each of a group of interested Section members has pledged himself to entertain once each year a Branch member as his guest at a Section dinner.

Light refreshments following a Branch meeting offer the opportunity for, and stimulate, sociability—a good quality which many engineers lack. The cost may be kept so low as not to be a burden on the treasury, and yet the purpose accomplished.

At one university I visited, an Engineer's Lounging Room was provided and furnished through the co-operation of the university authorities and the other engineering society branches.

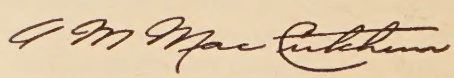
One of the most interesting and stimulating functions at the District meeting held in Dallas was the luncheon of the Branch chairmen, secretaries, and counselors. The counselor participated only by introducing the Branch chairman, who told of the plans for the future and the accomplishments of the past. Each of the 13 Branches was represented, and the 13 chairmen limited their remarks to a total of 45 minutes, each one telling something of interest to all.

In one of the schools, I found an engineering society to which all upper classmen were eligible. No junior or senior was denied the advantage and opportunity of an organized technical activity. This university engineering society was divided into groups, corresponding to the national professional engineering societies. Within the general society was developed the professional consciousness so desirable, and joint meetings were held treating economic and social responsibilities of the engineer. Once each year a purely social meeting was held. At this university, one evening a month was designated as Engineers' Night, and the other student organizations studiously avoided any conflicting activities. On Engineers' Night there was held either a joint meeting with all members of the engineering society free to participate, or simultaneous group meetings, with each devoted to a subject peculiarly interesting to that group. Contact with the national engineering society was maintained through the corresponding branch. With such an organization, possibly 4 evenings a year might be devoted to joint meetings and the presentation of general subjects, and 5 evenings devoted to parallel group meetings, featuring the presentation of specialized technical subjects. A joint meeting, with its consequently larger audience, is particularly suitable for an address by an outside engineer, or by a professor from the same or another technical school. Under this type of organization, I suggest the following as a typical Branch program.

No.	*Class*	*Speaker*	*Type of Subject*
1.	Joint	Professor	"The Problems of a Student Engineer"
2.	Branch	Outside Engineer	"What My Company Expects of a Young Engineer"
3.	Joint	Social	"Skits of the Anvil or Gridiron Variety"
4.	Branch	Student	"Description of an Interesting Engineering Test or Problem"
5.	Branch	Student	"Paper on Some Phase of Electronics"
6.	Joint	Outside Engineer	"The Engineer's Opportunities and Responsibilities"
7.	Branch	Graduate Student	"Presentation of a Research Problem"
8.	Branch	Outside Engineer	"Description of Interesting Installation, Application or Research Problem"
9.	Joint	Students	"Several Demonstrations"

As you study this program, you will note that no student is asked to prepare a paper before the fourth meeting, by which time the interst in the engineering society and Branch activities would have been stimulated by 2 good lectures and one social meeting. The closing meeting would be devoted to several technical demonstrations presented by the various divisions. To this unusually interesting meeting all of the sophomores and freshmen might be invited. The program would have been built up to a fine climax, and the enthusiasm and interest of this last meeting would assure a successful following year for each division.

In the training of the young engineer, the American Institute of Electrical Engineers and the other professional societies are privileged to play an important part. Of this they should be deeply conscious and should meet fully their obligations and embrace their opportunities. The student engineer, in relation to his group and his college, is quite analogous to the graduate engineer in his relation to society. There is a growing feeling that the graduate engineer has not always fully met his responsibilities and risen to his opportunities; that he has not always recognized his social and economic responsibilities. Many engineers have failed to realize that the best idea is of little value unless it is so convincingly presented to others that they accept it and assist in its execution. A compromise plan which is accepted and produces results is far better than the most brilliant individual plan which is neither accepted nor adopted. All engineers need training in the convincing expression of their thought. They should listen to the ideas of others and endeavor to see their viewpoints; should judicially weigh all expressed thoughts as evidence, and select that which is sound for combination with their own views; and should be able to express convincingly a logical conclusion. The development of a unified professional consciousness is of great importance, for then the profession may better serve humanity. Contact between older and younger engineers is stimulating to both. Each has much of value to the other—knowledge, experience, professional standing, and resources on the one side; youth, eagerness, enthusiasm, and a fresh viewpoint on the other. The branch of a national engineering society is a medium through which these needs of a student engineer should be met.



The Perfect Reading Page

By MATTHEW LUCKIESH
MEMBER AIEE

With the January 1937 issue, ELECTRICAL ENGINEERING presented to its readers the "easy reading" page. This article presents a discussion of the factors that would influence the production of a perfect reading page, and an opinion, founded upon scientific research, concerning this "easy reading" page as an approximation of the theoretical ideal.

DIFFERENCES of opinion cease to exist when adequate knowledge is available. Although this ideal stage has not been reached for the perfect reading page, great advancement has been made recently in the science of seeing. So long as opinions are based merely upon the science of vision, they must remain opinions because the basis is inadequate. Seeing is an activity of human beings; vision is merely an ability of eyes and the visual sense. Seeing involves the end products of human efficiency, behavior, and welfare.* It considers human beings as seeing machines and relegates eyes or the visual sense to the status of a part of the machine. Abuse of eyes is one of the consequences of unnaturally close and prolonged visual tasks imposed by civilization; however, much control can be exercised over certain factors, such as printing and lighting, to reduce the severity of visual tasks and the unnecessary waste of human resources.

The visibility of objects depends primarily upon

1. Size of the critical details.
2. Contrast between the object and background.
3. Brightness of the object and background, which depends upon the reflection factor and intensity of illumination.
4. Time available for recognizing the object.

In general, the theoretically ideal printed page results from

1. Large type of the most legible style.
2. Paper of high reflection factor and dull surface. If it is tinted, it should be optically and aesthetically satisfactory.
3. High level of illumination comparable to that in the shade of a tree or porch.
4. Time usually is not of great importance, if other factors are satisfactory.

Before considering the ideal printed page from a practical viewpoint, the process of reading should be considered. The focus of the eyes passes along the printed line in a series of leaps. Inasmuch as the movement of the eyes does not produce any apparent blurring, the eyes are assumed to be in some manner anesthetized during rapid motion. If one sees only when the eyes are at rest, the duration of the fixational pause is important. This has been found to vary chiefly between 0.07 and 0.30 second. These values are of importance in considering cases in which split seconds are important, but are merely of passing interest for the present.

Reading is done by swallows, as in drinking water. Words, or even groups of them, are seen at each pause. The number of stops made in reading a line depends upon visibility, familiarity, practice, and intelligence; consequently, the distinguishing of a critical detail, such as the space between the dot and the body of the letter *i*, may appear to be of little or no importance. Details remain of utmost fundamental importance, however, as typographical errors adequately testify. These details seem to dwindle in importance only through extensive practice in reading; in fact, seeing is very largely learning. Human beings learned to see things out in space before thinking became a conscious act.

Components of the Perfect Reading Page

A scientific analysis of visibility and the results of seeing show that the fundamental factors already listed are the basis of ease of seeing and, therefore, of the perfect reading page.

By omitting some of the tedious steps in considering type size, 12-point type may be concluded to be quite satisfactory for continued reading. Newspapers commonly are set in 8-point type, with parts of them in 6-point type. These small sizes, combined with paper of poor quality and generally meager intensities of illumination, make newspaper reading a severe visual task. The effect of type style on legibility is a complex matter, but long experience has evolved satisfactory styles devoid of needless details and with an openness necessary for good legibility. Obviously, the size of type determines the amount of matter that can be printed upon a page. This is an important consideration for publications such as newspapers, but such economy in space should not be carried too far in journals, and particularly in books.

The contrast between the print and the page depends upon the blackness of the ink and the reflection factor of the paper. Perfect black on perfect white does not exist. This would be 100 per cent contrast as computed on the basis of the ratio

$$100 \times \frac{\text{Background brightness} - \text{Object brightness}}{\text{Background brightness}}$$

An article written especially for ELECTRICAL ENGINEERING.

MATTHEW LUCKIESH is director of the lighting research laboratory General Electric Company, Cleveland, Ohio. Doctor Luckiesh received the degrees of bachelor of science in electrical engineering (1909) and doctor of engineering (1935) at Purdue University; electrical engineer (1912) and doctor of science (1926) at Iowa State College; and master of science (1911) at the State University of Iowa. He has been associated with the Nela Park research laboratories of the General Electric Company since 1910, having served successively as physicist, director of applied science, and director of lighting research. Doctor Luckiesh has received several honors for his work in color and lighting research, and has written many books and technical papers.

* SEEING—A PARTNERSHIP OF LIGHTING AND VISION (a book), M. Luckiesh and Frank K. Moss. Williams and Wilkins Company, Baltimore, Md., 1931.

Usually the nearest approach is a contrast of about 97 per cent. For a telephone directory the contrast between the print and paper commonly is about 80 per cent, and for the better examples of newsprint about 85 per cent.

Any color, even a light tint, added to white paper decreases the contrast slightly; however, the extent to which this decrease causes a decrease in visibility should be considered in weighing this against other considerations. There can be no justification for the use of highly colored paper for pages that must be read for extended periods; furthermore, from purely the optics of the eye, blue, violet, purple, and pink papers are inadvisable. Normal eyes cannot focus blue light at the usual reading distance. Adequate experiments have shown that elimination of the blue and violet components of light does not decrease visibility appreciably, because the resultant loss of light is compensated by increased definition of the image. For this reason alone, a yellowish tint is better than any other.

The loss in contrast is very slight in a white paper tinted yellow, and is less in ordinary artificial light than in daylight. Although contrast is very important in the visibility of objects, it is of only slight importance in the range of high contrasts; therefore, any other small advantage gained by the use of a paper of yellowish tint overcomes the loss caused by the slight decrease in contrast.

The reflection factor of a paper having a slight yellowish tint is a few per cent less than it would be if the tint were eliminated, thus reducing the brightness of the paper under a given intensity of illumination by an amount exactly proportional to the reduction in reflection factor. An appreciable change in visibility requires such a large change in brightness, however, that the reduction caused by a slightly lowered reflection factor is negligible, particularly when the intensity of illumination is sufficient for ease of seeing.

The perfect reading page, so far as the reader is concerned, depends upon lighting as well as upon the paper or printing. Glossy paper may reflect bright, imperfect images into the eye; dull paper is ideal, but if half tones must be considered, the practical ideal may be different. Dull papers nevertheless have been developed for half-tone printing without too much compromise between the reader, printer, and paper manufacturer.

Ease of reading printed matter depends upon visibility, but manifests itself remotely from this. The writer and his colleague, Frank K. Moss, have measured successfully the nervous muscular tension indicated by the finger tips for a large number of subjects over a range of illumination intensities of from one to 100 foot-candles. One foot-candle, which is the illumination one foot from a candle, is a common illumination indoors. The general average in the indoor world is less than 5 foot-candles where reading is done. Near a window in the daytime there is commonly an illumination of several hundred foot-candles.

Experiments have indicated that while the subjects read a book printed in 12-point type on excellent dull, white paper, the ease of reading continues to increase up to at least 1,000 foot-candles. No one is conscious of this nervous muscular tension, except in special cases of difficult visual work; but it results from all visual work and represents waste of human resources. The 12-point type could be read at one foot-candle.

This and many other researches prove that ease of reading cannot be judged by visibility, and the mere possibility of seeing provides no reason for believing that further improvement in seeing is of no value. This new knowledge arose directly from an expansion of the concept of vision into one of seeing, and from a consideration of human seeing machines, instead of merely eyes.

Whether refinements of this new technique could show appreciable difference in the ease of seeing objects against a yellowish tint, as compared with a white one, is at present unknown; however, some other reasons for using a slightly yellowish paper seem to be adequate. It does not decrease visibility appreciably because of its slightly lower reflection factor and the consequent slightly lower contrast; moreover, its color is in the right direction from the viewpoint of chromatic aberration of the eye.

Aside from the foregoing considerations, the aesthetic or, more broadly, psychological effects are important. From an aesthetic point of view the author prefers a slightly yellowish tint, and many other persons have expressed a similar preference. Psychologically, the subtle warmth of the yellowish tint has something in its favor. White has much virtue in its place and, in fact, is symbolic of virtue; but white has disappeared from many places in which it dominated until a few years ago. Modern hospitals have eliminated it to a great extent, and modern kitchens and bathrooms have little of it. The decorative schemes of hospitals, kitchens, and bathrooms consequently have reverted to their proper function—to please aesthetically and psychologically.

Electrical Engineering's "Easy Reading" Page

The reflection factors of the paper formerly used in Electrical Engineering and of the present sepia-tinted paper are 76 and 73 per cent, respectively, for ordinary tungsten-filament light. The difference is slightly greater for daylight. Assuming the same quality of ink and printing, this difference is not sufficient to produce an appreciable difference in contrast. In fact, measurements made with the Luckiesh-Moss visibility meter of the visibility of print of the same size of type on the former and present papers revealed no significant difference; therefore, the change has been made with no appreciable sacrifice in measurable factors. In other words, whatever the gain (or loss) may be in the aesthetic comfort and possibly in physical comfort is achieved without other sacrifices. The appraisal of the factors that cannot be measured at present must be left to the readers. Their present, or initial, reactions will be interesting to compare with their reactions a few months hence. Certainly there is a striking difference in the appearance of the 2 papers, considering the slight difference in brightness or reflection factor. Many white papers have reflection

factors of from 80 to 85 per cent, and there would be an appreciable difference in the visibility of a given black print on them and on this sepia-tinted paper, which has a reflection factor of 73 per cent. The present discussion, however, refers to the paper formerly used and not to any other so-called white paper. Incidentally, all these measurements were made with papers backed up by several thicknesses, thus simulating actual reading conditions for a book or magazine.

Regardless of initial reactions to a yellowish-tinted paper, one should first give consideration to the general reaction against white. As to the influence of aesthetic and psychological effects upon the efficiency and behavior of human beings there can be no doubt on the part of those who understand that human beings are seeing machines. Feelings are just as real as any reality, and one can be just as unconscious of them as of other results of seeing, such as nervous muscular tension. To recapitulate, there is some scientific evidence, however slight, in favor of a paper of yellowish tint, and from the aesthetic and psychological viewpoints also it may have something in its favor. At any rate, knowledge springs both from controlled researches and mass experience. The present attempt to produce a perfect reading page provides opportunities for demonstrating or acquiring knowledge along these 2 general lines.

Charles Le Geyt Fortescue

and His Contributions to the Electrical Industry

By C. A. POWEL
MEMBER AIEE

CHARLES LE GEYT FORTESCUE will long be remembered as an engineer well-known for his technical achievements and well-loved for his qualities as a man. Some of his accomplishments have been so outstanding that it seems worth while calling attention to their value and to the extent to which they have been useful in extending human knowledge and lightening the labor of other engineers in his own and succeeding generations.

In the appreciation of the present generation of electrical engineers, Doctor Fortescue will be known for 3 principal fields of work. These probably would be his development of the method of symmetrical co-ordinates used for the solution of unbalanced polyphase circuits; his analysis of the factors affecting stability of transmission systems; and his philosophy of lightning protection and his contribution to the theory of direct strokes. A group of engineers a little earlier in time probably would credit him with his work in rationalizing the design of transformers; with his studies of dielectric phenomena which led to the adoption of the sphere gap as a standard of high voltage measurement; and with his work on the development of line insulators on the so-called "faradoid" principle.

These and many similar accomplishments indicate that his interests lay principally in the transmission of power and its related problems, a field which has expanded enormously since he entered the profession.

Fortescue was born at York Factory, Manitoba, Canada, November 11, 1876, where his father was chief factor of the Hudson Bay Company. He came of an old Devonshire family that as far back as the fifteenth century became prominent in literature. Educated at Dawlish, Devon, England, and at Queens University, Kingston, Ontario, Canada, he was Queens' first graduate in electrical engineering, and it used to be remarked that "they started with a good one." In recognition of his outstanding contributions to electrical engineering, his alma mater awarded him, in 1929, an honorary degree of doctor of laws. On graduation in 1898 he joined the Westinghouse Electric & Manufacturing Company at East Pittsburgh, Pa., where he remained throughout his professional career.

Doctor Fortescue became an Associate member of the AIEE in 1903 and was transferred to the grade of Fellow in 1921. He served on the following Institute committees: power transmission and distribution, 1925–29 and 1932–36; telegraphy and telephony (now communication) 1914–17; electrophysics, 1916–17, 1920, 1922–24, 1927–31. He was the author or co-author of 23 technical papers and numerous discussions published in the AIEE TRANSACTIONS over a period of 27 years.

Starting as an apprentice in the Westinghouse shop, he

Written especially for ELECTRICAL ENGINEERING.

C. A. POWEL is manager of the central station engineering department of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., and was associated with Doctor Fortescue for many years. He is a director of the AIEE and has been a member of the Institute's committee on power generation since 1933; he was chairman of the AIEE Pittsburgh Section, 1935–36.

was quickly noticed by B. G. Lamme, who happened to be in need of a young assistant to devise new designs and new methods of building armature coils. The problem of meshing together the ends of armature coils—primarily a problem in 3-dimension geometry—was a fertile field in which the mathematically minded young engineer had full scope for imagination and for adapting theoretical schemes to practical necessities. His success in working out original short-cut methods of designing coils with short ends, requiring very little clearance, marked him as having ingenuity to an unusual degree, and he was transferred to the transformer department to see what could be done to rationalize the design of transformers, which at that time, as Fortescue himself used to say, "was more of an art than a science." His success in this work perhaps is best demonstrated by the section prepared by him for the "Standard Handbook for Electrical Engineers" which follows closely the principles developed by him in the years spent on this work.

About 1909 Fortescue became imbued with the importance of the dielectric field in transformers. He claimed that the so-called creepage effect was not a characteristic of the insulation surface itself but of the dielectric field in which the surface lay. Assisted by S. W. Farnsworth, development work was undertaken to prove or disprove this idea and to lay out a high-voltage transformer design in which the dielectric field was taken into account. This resulted in 2 very noteworthy papers published in the AIEE TRANSACTIONS of 1913:

AIR AS AN INSULATOR WHEN IN THE PRESENCE OF INSULATING BODIES OF HIGHER SPECIFIC INDUCTIVE CAPACITY by C. L. Fortescue and S. W. Farnsworth, pages 893–906.

THE APPLICATION OF A THEOREM OF ELECTROSTATICS TO INSULATION PROBLEMS by C. L. Fortescue, pages 907–25.

An important result of this research was the proposal that the sphere gap should be used as a standard for measuring high voltages. This was done in 2 papers, also published in 1913 in the AIEE TRANSACTIONS:

THE SPHERE SPARK GAP by S. W. Farnsworth and C. L. Fortescue, pages 733–7.

CALIBRATION OF THE SPHERE GAP VOLTMETER by L. W. Chubb and C. L. Fortescue, pages 739–48.

This proposal was accepted and today has become standard practice throughout the world.

About this time Fortescue turned his attention to railway electrification and the related power-supply problems. For heavy traction, the transmission lines and the trolley-rail circuits with their interconnecting transformers constituted a network of considerable complexity; and since there was then practically no literature on networks, he applied himself to their solution and formulated a number of network theorems. One of these was the theorem of equivalent loads by which a load at any point on a railroad could be replaced by 2 loads at adjacent substations inversely proportional to the impedance of the trolley-track circuit from the 2 substations to the actual load point. Another was that of superimposed solutions, which permits the determination of voltage drop to a given point by adding the separately computed voltage drops to that point due to loads at each of many load points. In the same way, the current in any branch of the network may be determined by adding the separately determined currents in that branch due to each particular load. These theorems are rigorously correct; they serve to reduce a complicated network to a very simple one, thus permitting one to make calculations in a very few hours that formerly would have required days.

Fortescue was active on the various a-c railway electrifications, including particularly those of the New York, New Haven and Hartford, Norfolk and Western, and Pennsylvania railroads, and did much to rationalize the design of railway power-supply systems and to set the reactance proportions which obtain at the present time. He gave attention to the problems of inductive co-ordination with communication and railway-signal circuits, and in connection with the latter he contributed the resonant impedance bond. He proposed several new schemes of phase balancing and phase conversion, and among others the series type of phase balancer which was the first scheme to provide balancing action without automatic devices such as voltage regulators.

It was while working on these unbalanced railway-supply circuits that Fortescue conceived the possibility of a mathematical analysis that led to the invention of symmetrical co-ordinates. In simple mathematical terms it consists of a system of generalized Lagrangian co-ordinates especially suitable to all types of polyphase problems. His paper

METHOD OF SYMMETRICAL CO-ORDINATES APPLIED TO THE SOLUTION OF POLYPHASE NETWORKS, AIEE TRANSACTIONS, volume 37, 1918, pages 1027–1115

is one of the milestones of the industry. This mathematical tool is now established in all countries as the only effective method of analyzing general polyphase network problems. For his development of this theory Doctor Fortescue received the Elliott Cresson Gold Medal of the Franklin Institute.

With the advent of the interconnection of power systems during and following the World War, Fortescue began to interest himself in the problems of the maintenance of synchronism over long transmission lines. Here again in his search for methods of simplifying the calculations he and his associates broke new ground by bringing out the so-called power-angle diagram which today is the form generally used for expressing stability.

Following the establishment of these interconnecting transmission lines, their principal drawback was found to be their susceptibility to outage due to lightning. This led Fortescue to turn his attention to the problem of methods of protection against lightning. In 1923, J. F. Peters, now consulting engineer of the Westinghouse company, brought out the klydonograph which was the first instrument suitable for field studies of lightning surges. With this device studies were made under the direction of Doctor Fortescue in co-operation with power companies, and the results of these gave a great deal of information regarding lightning surges which previously had been unsuspected. Thus encouraged, Fortescue undertook a further series of tests using the Norinder type of oscillograph,

the results of which confirmed the ideas Fortescue had been building up, and in a paper

Theoretical and Field Investigations of Lightning, AIEE Transactions, volume 48, 1929, pages 449–68

he promulgated his idea that induced strokes of lightning were not in general harmful to transmission lines and that protection against direct strokes was quite feasible.

Doctor Fortescue was a prolific inventor, the recipient of some 185 patents. Perhaps his outstanding characteristic as an inventor was his fondness for generalized theorization, which led him away from beaten paths and produced many inventions of fundamental and outstanding character, leaving to others the task of perfecting details as to methods for carrying them out. Among the important Fortescue patents might be mentioned those on the design of transformer windings to distribute properly the electrostatic stress through the insulation; thermoelectric protection of distribution transformers against burnouts and secondary short circuits; the high-voltage condenser-type bushing; shunt and series phase-balancers for railway systems; high-speed d-c circuit breakers with impulse tripping for d-c railways; the application of the "faradoid" principle to porcelain insulator design whereby the insulator surfaces were shaped to conform to the electrostatic field about the insulator; control grids for vapor-filled converters; and interphase transformers for vapor-filled converters.

His technical achievements, great as they were, did not account for his great popularity. He was human, sometimes beautifully inconsistent in little things. On a fishing trip he was complaining about lack of regulation in the United States which permitted any number of fishermen on a given stream. "Now in England," he said, "a stream like this would be fished by but one man who had bought the fishing rights on the stream." "Of course," rejoined another of the party, "you assume that you would be that one man."

He often worked on "hunches," but with the unerring instinct of genius. He had a feeling of what the answer to a problem should be and backed his "hunches" with logic. It is sometimes much easier to solve a problem backwards by assuming an answer.

His company always was sought. Aside from his wide technical interests, his reading and contemplations covered the arts and social sciences. An interesting conversationalist, "Forty," as he was familiarly known, always had a fresh and original point of view. He thoroughly enjoyed a story, both in the hearing and the telling. A favorite with old and young, his association with young engineers seemed to affect him as Ponce's waters and accounted for the enthusiasm that was so characteristically "Forty," even during the debility occasioned by his last illness.

His influence was felt in every group with which he worked. Doctor Joseph Slepian, now consulting research engineer of the Westinghouse company, has said that he received more inspiration from his contact with Fortescue than with any other man in the company. Working with a group, his personality was impressed both upon his work and upon his associates, frequently to the extent that a group's labor came to be associated only with the name of Fortescue. Outside engineers also sought his advice and counsel. His integrity and honest judgment enhanced still further his technical recommendations.

200-Inch Telescope Being Welded Electrically

Mounting structure for the 200-inch telescope being built on Mt. Palomar, in Southern California, will consist of electric-arc-welded units

A BILLION light-years is the distance to which scientists and astronomers estimate that they will be able to explore the universe when the new 200-inch reflecting-type telescope, largest in the world, is completed on Mt. Palomar, Calif. This is twice the range of the next largest telescope in existence, the 100-inch instrument at Mt. Wilson, Calif. (A light-year is the distance traversed by light in a year and is approximately 6×10^{12} miles.) Mt. Palomar, which is about 90 miles from Los Angeles, was selected because of its ideal weather conditions and its isolation. In addition to a new observatory to house the huge telescope, the project includes construction of a new 20-mile road, a new community for the operating staff, several smaller domes, power plant, radio station, million-gallon water reservoir, and an airplane landing field. Headquarters of the observatory will be on the campus of the California Institute of Technology, Pasadena, which institution will supervise its operation.

Originally conceived by Doctor George Ellery Hale in 1918, immediately following completion of the 100-inch Mt. Wilson telescope, actual work on the project began in 1928 when a grant of $6,000,000 was made by the Rockefeller Foundation. It is expected to be completed by 1940. The structure for supporting the telescope is being built in the South Philadelphia Works of the Westinghouse Electric and Manufacturing Company. It consists of

Prepared especially for Electrical Engineering from information supplied by the Westinghouse Electric & Manufacturing Company, South Philadelphia (Pa.) Works, and particularly that compiled by J. Ormondroyd, experimental division engineer (now with University of Michigan, Ann Arbor) and Norman L. Mochel, metallurgical engineer.

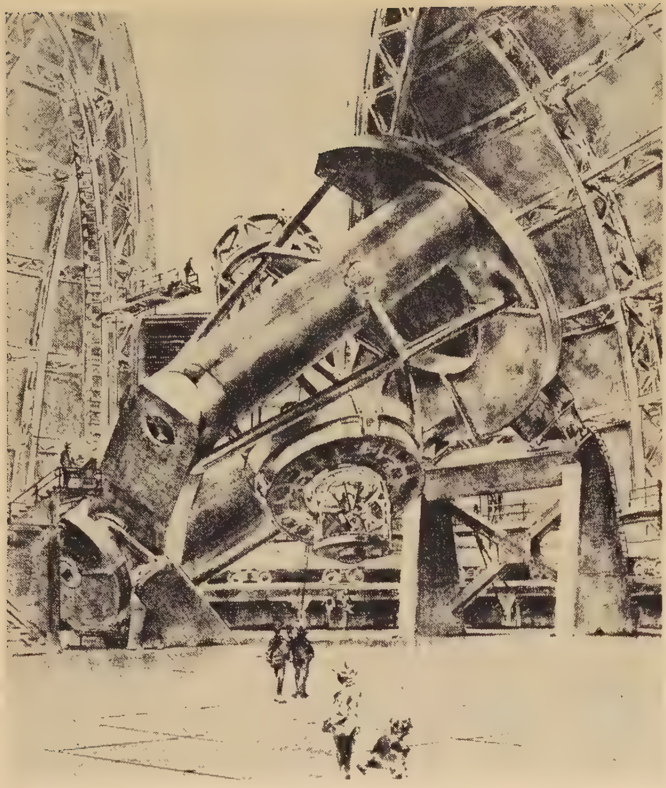


Figure 1. Artist's conception of the 200-inch Mt. Palomar telescope as it will appear when completed

several electric-arc-welded units which will be shipped by water to the Pacific Coast and thence by special trucks to the Mt. Palomar site, and which will be bolted together there. The 200-inch glass mirror, which will be the last unit to be installed in the telescope, is now being ground in the optical shop of the California Institute of Technology.

The magnitude of the 200-inch telescope perhaps can be understood best by comparing it with the 100-inch Mt. Wilson telescope (see table I). Its over-all height will be approximately 75 feet. The method of controlling the instrument has not been determined but, undoubtedly it will be electrical. Some conception of the control problem may be gained when it is realized that most of the observations to be made by the telescope will be upon photographic plates and that some exposures will require many hours each. The control mechanism must keep the telescope focused accurately throughout the entire period of exposure.

Mounting Will Consist of 2 Main Parts

The mounting for the telescope will consist of 2 parts: a tube, and a cradle or yoke which will carry the tube (see figures 1 and 2). The tube, which will serve as the supporting structure for the principal optical elements, will rotate about 2 ball-bearing trunnions supported in the horseshoe-shaped yoke. Its range of rotation will be from the southern horizon to the north celestial pole. The axis around which it will rotate relative to the supporting cradle is known as the declination axis.

The yoke will turn about an axis that is perpendicular to the declination axis. This axis, lying in the meridian (north-south) plane, will be placed at an angle to the horizontal equal to the latitude of the observatory, which will make the axis parallel to the polar axis of the earth, and will point it toward the celestial pole. For this reason, this axis is called the polar axis of the telescope. The yoke will rotate 105 degrees to either side of the meridian plane.

These 2 rotations around the polar and declination axes will permit the telescope to be held on any celestial object within its range. Continuous rotation about the polar axis at the rotational speed of the earth, but in the opposite direction, will keep the tube oriented at a fixed angle relative to the "fixed stars."

The polar-axis bearings, which support the yoke, will be unique in telescope design. To insure smoothness of rotation, the whole million-pound telescope will be floated on oil under high pressure, at both the north and south ends. At the north end the "horseshoe" will be supported on 4 pads. In the surface of each pad will be 4 symmetrically spaced recesses with central oil inlets. Oil flowing through these inlets at a pressure of from 250 to 300 pounds per square inch will support the telescope. Oil will flow continuously through a gap of from 0.003 to 0.005 inch between the pad surface and the outer periphery of the "horseshoe." At the south end, the single bearing will be a ball and socket 8 feet in diameter with oil inlets so spaced that the radial and thrust loads of the telescope will be supported with the ball held about 0.005 inch away from the socket.

The total viscous friction torque of these 2 bearings at the operating speed of one revolution per day will be of the order of 50 foot-pounds. This figure becomes remarkable only when it is realized that conventional roller and ball bearing supports would lead to a friction torque of 30,000 foot-pounds, 600 times the oil-pad friction torque. The smallness of this friction is emphasized by the fact the telescope can be kept rotating at one revolution per day by the amazingly small output of about 1/160,000 horsepower. For quick setting, however, a driving motor of at least $^{1}/_{2}$ horsepower will be required.

Table I. Comparison of 200-Inch Mt. Palomar and 100-Inch Mt. Wilson Telescopes

Item	Mt. Palomar	Mt. Wilson
Type of telescope	Reflecting	Reflecting
Diameter of mirror, inches	200	100
Approximate weight, pounds	1,000,000	125,000
Approximate cost, dollars	6,000,000	Less than 1,000,000
Fabrication of structure	Welded	Riveted
Focal length of mirror, inches	666	500
Relative aperture	3.33	5
Yoke bearings	Oil pad	Mercury float
Maximum range, light-years	*1,000,000,000	500,000,000

*Estimated.

Arc Welding Being Employed Throughout

The decision to employ arc welding so extensively in the construction of the tube and mounting of the 200-inch telescope is another outstanding example of the engineer's confidence in the welding art. There is nothing of an experimental nature, however, in the adoption of welded construction for the various members of the telescope. Other structures of comparable size and complexity, and of like value and importance, have been fabricated successfully by this method.

Steel plates, bars, structural shapes, and a few steel forgings are being welded together to form the member parts of the telescope. The size and shape of these member parts naturally reflect the general design, but have also been influenced by such practical considerations as the availability of material, machining facilities, transportation, and the necessity for minimizing internal stresses and resulting distortions.

It must be understood that the various member parts are being prepared by machining for bolting together at Mt. Palomar. Frequent references to all-welded construction may have given the erroneous impression that member parts were to be joined on location by welding. It is true that in many large structures, member parts have been and are being joined by welding on location. In such structures, however, the construction and intended service invariably are such as to tolerate distortions that may take place during welding or during the useful life of the structures, or in which the presence of variable and unknown degrees of internal stress are of little concern. Obviously such conditions could not be tolerated in the 200-inch telescope.

In any discussion of welding, one is naturally interested in the materials that must submit to welding. Again one encounters an erroneous impression—that a telescope must be constructed largely of special alloys that have low expansivity. Although it is true that some materials of this type are being used in connection with the mirror and other optical parts, most of the material being used for the tube and mounting is quite ordinary mild carbon steel. All the materials being welded are of standard commercial grades—an important practical consideration.

All plates, bars, and structural shapes have been rolled by one supplier from specially selected heats, to give the greatest possible uniformity of composition. Plates less than $1^1/_2$ inches thick were made of the usual flange quality of steel plate, similar to that covered by ASTM Specification *A*-70. All such steel for the tube was made from a single heat, specially melted for the purpose. Plates $1^1/_2$ inches thick and more were rolled from silicon-killed steel poured into hot-top ingots, to guarantee soundness of section. This steel is similar to grade *A*, ASTM Specification *A*-150. Two carbon-molybdenum steel forgings are being

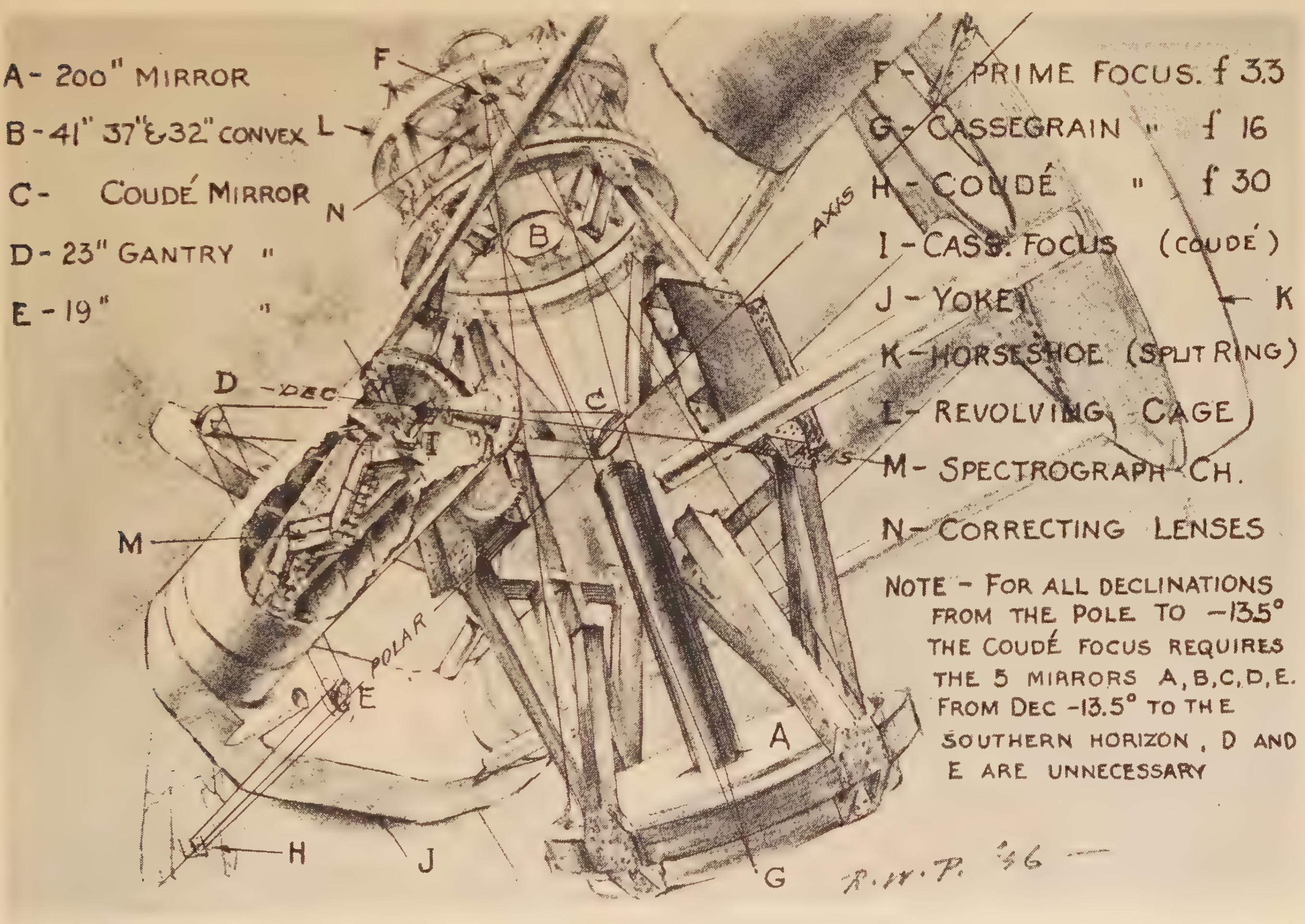


Figure 2. Diagram of telescope showing details of design

used in fabricating the declination bearing housing.

Arc welding only is being employed, and heavily coated electrodes of the mineral-coating or slag-producing type are being used. These are of but 2 makes, both of the highest quality available. It is well recognized today that electrodes can be devised that will meet best some given condition of deposition. Full advantage of this has been taken and 3 kinds of electrodes, as regards position of deposition, have been used. One was used for all down-hand butt welds; another for all down-hand or horizontal fillet welds; and yet another for welds that of necessity had to be made in a vertical position. Overhead welding has been avoided. The electrodes are of such nature that they are equally satisfactory with either d-c or a-c welding apparatus. Both are being used throughout; a-c welding was found to be especially useful for welding into corners.

All welding on the tube parts and to date on the "horseshoe" has been manual welding. The 2 declination-bearing housings were produced using automatic welding for the longitudinal and external circumferential welds.

Figure 3 shows a stage in the fabrication of the prime-focus cage. The lower main ring of the cage was formed on the floor plate and the uprights, formed elsewhere as detail parts, were assembled as shown. The ring is approximately 22 feet in outside diameter and the cage is roughly 12 feet long with the top ring in place. The gauge for controlling the proper radius and for accurately locating the pieces of tubing that are in evidence, may be noted. The simple method for supporting and clamping the ring both inside and out is shown. The use of intermittent welding may be noted in most of the parts.

Figure 4 shows work in progress in the fabrication of one of the end sections of the "horseshoe." This "horseshoe" has an outside diameter of approximately 46 feet. The plates used to form the inner and outer bands were preformed, and are $4^1/_2$ inches thick and 60 inches wide. One side plate was formed first. This plate was then clamped down and the inner and outer bands moved into position and clamped around the outside. Clamping blocks were welded to the bands as shown. The internal plates and reinforcing members were fitted in place and secured by tack welding. After properly fitting the cellular or box-like structures that fasten to the outer band and fixing the various component parts by welding a bar across them, they were removed from the main part and welded under the most ideal conditions on the floor. This had a double advantage: It permitted turning them in any position to get the best welding, and it avoided undue heating and stressing of the main members by the considerable amount of welding necessary. There are 5 of these sub-assemblies, 2 of which are shown in place in figure 4.

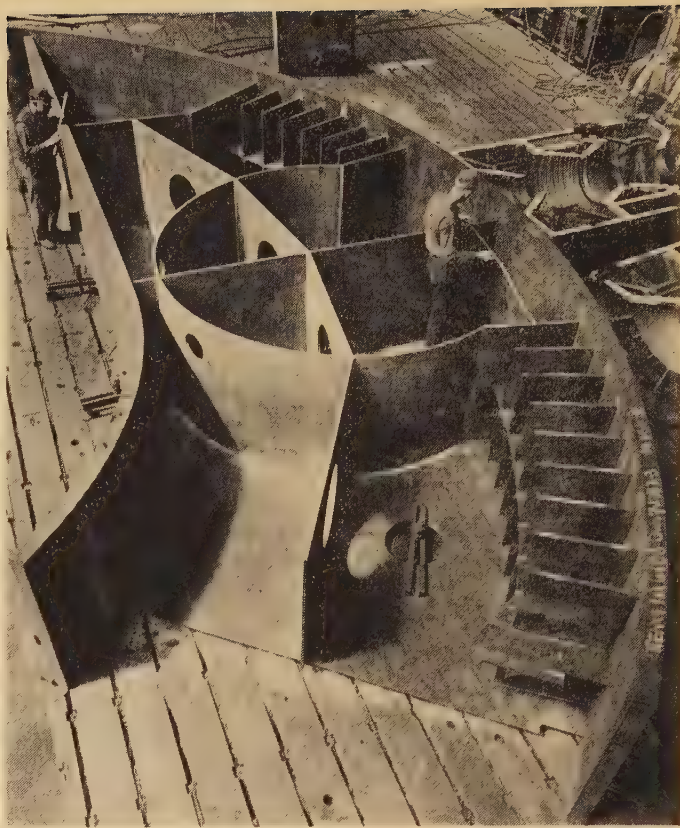


Figure 4. Early stage in fabrication of one section of the yoke "horseshoe"

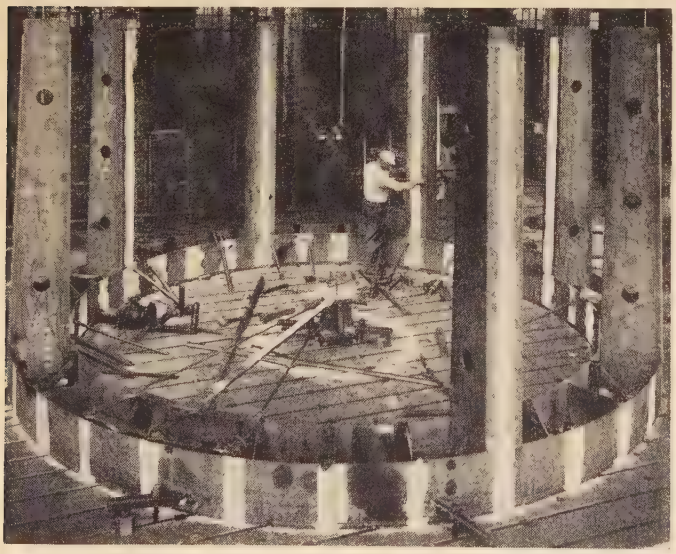


Figure 3. Fabrication of bottom ring and uprights of prime-focus cage. Note that clamping blocks, struts, and stays are attached exactly where wanted by welding; they are readily removed later

All the telescope parts are being carefully annealed to relieve internal stresses. A double annealing cycle is being used: first heating to from 1,150 to 1,200 degrees Fahrenheit, holding for a period of 3 hours for the first one inch of thickness or fraction thereof, followed by a slow cooling in the furnace until the temperature has fallen below 600 degrees Fahrenheit; and then repeating this cycle in its entirety and co ling below 300 degrees Fahrenheit before the furnace doors are opened.

As an example of the accuracy with which the parts were held to size throughout welding and annealing, when the prime-focus cage was placed on the boring mill to face the lower end where it bolts to the top ring of the tube, the departure from roundness was not greater than $^1/_{16}$ inch.

Electrical Computer Eliminates Calculations

Based upon an exact electrical analogy of a mechanical system, a specially constructed electrical computer eliminated many laborious calculations in designing the overhead catenary system for an extensive railroad electrification

By FRED H. HEDIN
ASSOCIATE AIEE

MANY engineering applications involve the solution of numerous laborious and repeated calculations of a similar nature. The design of the overhead catenary for an extensive railroad electrification, which is typical of such applications, involves the determination of the shape of a messenger cable for thousands of spans that differ only in length and in the location and values of the supported loads. During the design of a recent railroad electrification, a squad of from 15 to 20 men were continuously employed by the engineers on such calculations for a period of about 2 years. Both the volume and required accuracy of these calculations led to a search for some simple computing device whereby the most monotonous part of the calculations might be eliminated and the progress of the work expedited. The purpose of this article is to describe the computer which was developed for this purpose.

The Problem

As is well known, the contact wire of a catenary system is supported directly or indirectly by means of hangers from a messenger cable, which in turn is supported at intervals of from 200 to 300 feet on structures transverse to the tracks. For the modern high-speed electrification, where heavy currents are collected at speeds of the order of 90 miles per hour by means of the sliding contact of a pantagraph, it is of paramount importance that the riding contact wire be in nearly a horizontal plane, or if a change in elevation is necessary, that the change be smooth and gradual.

On tangent track, with no special work such as crossovers or turnouts, the computation of the shape of the loaded messenger, for the purpose of selecting hanger lengths to give a smooth-riding contact wire, is comparatively simple. Tables or templates are used, as the load is distributed uniformly and there is practically no error in the assumption that the messenger takes a parabolic shape.

However, at interlocking points and yards, the problem is much more difficult. The intersection of the catenary from different tracks, as well as the design of air breaks for sectionalizing purposes, requires that the contact wire be raised or lowered with respect to its normal riding datum, with resultant changes in messenger loading (since the contact wire is itself under high tension). Also the concentrated loads of sectionalizing insulators, which may amount to several hundred pounds, must be carried. The resultant shape of the messenger, under the various concentrated and distributed loads that may exist in a span, is no longer a smooth and simple mathematical curve and must be calculated by the laborious step-by-step moment method. The various spans usually have different loadings because of physical obstructions in locating structures and variations in existing track layout.

Not only are the computations laborious and monotonous, but they consume much time because of the added necessity for checking. It is difficult and very expensive to make field correction, because of the flexible nature of the catenary and because the installation may be made under an extreme temperature condition, which affects the messenger shape.

A typical span, selected from thousands of similar ones, is shown in figure 1(a). The messenger loading and shear diagrams also are shown in figure 1(b and c).

The problem therefore was essentially this: Given a flexible cable, strung at known tension, over a known span, between fixed supports, and subject to known vertical loads, at known points in the span; to develop a simple and accurate device to determine, quickly and automatically, the reactions at the supports and the complete shape of the cable. Further, the device must be equipped to handle variations in the given factors of tension and span length, as well as direction, location, and number of vertical loads.

Evolution of the Circuit

During the course of the search for a fundamental basis for such a computing device, the following analogy was visualized, more or less accidentally: First, referring to figure 2 (a), consider the simple case of a messenger of span L and given horizontal tension T, subjected to a single concentrated load W at any point in the span. Then the part of the load W carried at each messenger support (reactions), and the shear in the messenger is as shown. Then, consider the electrical analogy as shown in the simple circuit figure 2 (b). A resistor of any length, and of any uniform resistance per unit of length, has a current I supplied to it at the same relative point in its length as the mechanical load is in the messenger span.

Written especially for ELECTRICAL ENGINEERING.

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If the 2 ends of the resistor (or current divider) are tied together to a common return circuit, then the division of the current is as shown.

By comparison of (*a*) and (*b*) of figure 2, it is at once apparent that a useful analogy exists. The mechanical load W seems to divide and "flow" to each messenger support, exactly as though the messenger were a uniform resistance connected as shown in (*b*). Therefore, it can readily be seen that if a constant value of pounds per ampere is assumed, and if an ammeter is calibrated directly in pounds on that basis and connected as A_3 in figure 2 (*c*) and 2 similarly calibrated ammeters are inserted in the circuit as A_1 and A_2, and if the input (or "load") current is regulated by resistance R so that A_3 reads W pounds; then A_1 and A_2 will read, directly in pounds, the reactions R_1 and R_2.

This analogy was based upon the simplest kind of a span with only one concentrated load. The question that now naturally arises is whether the division will be made correctly should additional currents be supplied simultaneously to other points of the resistance divider, to represent other concentrated loads on the messenger. The messenger itself acts to distribute the various concentrated loads to each support exactly as though each load were acting alone on the messenger, the summation of each individual load's reaction being the total reaction at that support. It can be demonstrated by rigid proof that the electrical circuit as shown acts in an identical manner. This proof is somewhat involved for the purpose of this article, but it can be visualized partially by noting that, although there are various IR drops in various parts of the resistance divider due to the application of several "loads," nevertheless, if any point in the divider is considered as a point of application for still another "load," the total potential drop from the proposed point of application to either end of the divider tube is the same. Thus the existence of other "loads" on the resistance divider does not affect the correct distribution of a proposed additional "load" and only serves to require a little more "push" to get the load into the divider. This extra "push" is provided by cutting out a slight amount of additional resistance in the load-applying circuit. Since this resistance always is regulated to produce the correct "load" reading on the ammeter in its circuit, the final position of this uncalibrated load-regulating resistance is not important.

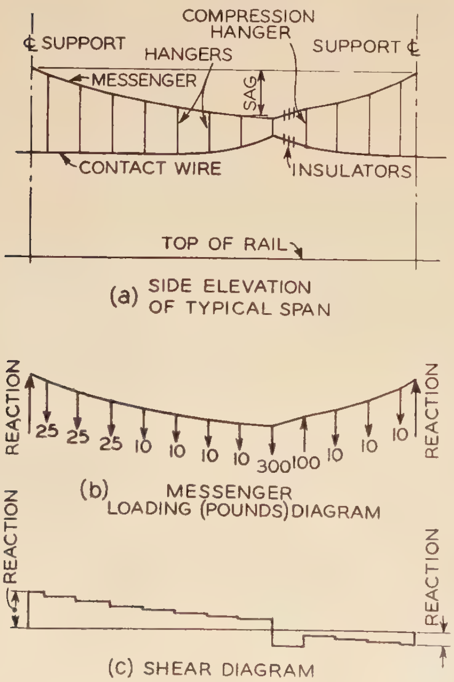

Figure 1. Typical catenary span to be solved on computer, showing construction, messenger loading, and shear diagrams

Another interesting fact revealed by comparing (*a*) and (*b*) of figure 2 is that the current distribution in the divider is identical with the shear diagram for the messenger. The current even reverses its direction at the same point as the shear passes through zero. This analogy is true for any number of applied loads on the messenger if corresponding "load" currents are supplied to the resistance divider.

From the foregoing facts, one more step now is possible. In a messenger span under given tension, the sag at various points is proportional to the total moment at these points. The moment involves load and length (moment arm). Similarly, the voltage drop from any point on the resistance divider to either end is dependent on the current (load) and resistance (length) of the section. Therefore it might be surmised that a definite relation exists between the sag at a given point on the messenger and the voltage drop from the end of the properly loaded resistance divider to a corresponding point on the divider. If this is investigated mathematically, the following formula results:

$$V = wpkT \times \text{sag in feet}$$

where

p is the relation between the length of the span and the length of the resistance divider in feet.
k is the amperes per pound used to calibrate the load and reaction meters.
w is the ohms per foot of the resistance divider.
T is the messenger tension.

The constants w and k may be incorporated in the calibration of the volmteter; the factors p and T, which are constant for a given problem but may vary in different problems, are calibrated into the voltmeter for the maximum span length and minimum tension (i.e., maximum sag) that are likely to occur. Then the voltmeter reading is reduced by a variable series resistor, calibrated in the ratio of tension to span length, for computing other problems involving greater messenger tension or shorter span, or both. Thus, the voltmeter will read the sag directly in feet if one end is permanently connected to the ends of the resistance divider and the other end arranged to contact the divider at any point where the corresponding messenger sag is desired.

Construction of Computer

A computer was designed and constructed according to the described electromechanical analogy. The complete wiring diagram is shown in figure 3, and the completed computer is shown in figures 4 and 5.

A choice of design constants was available, and the

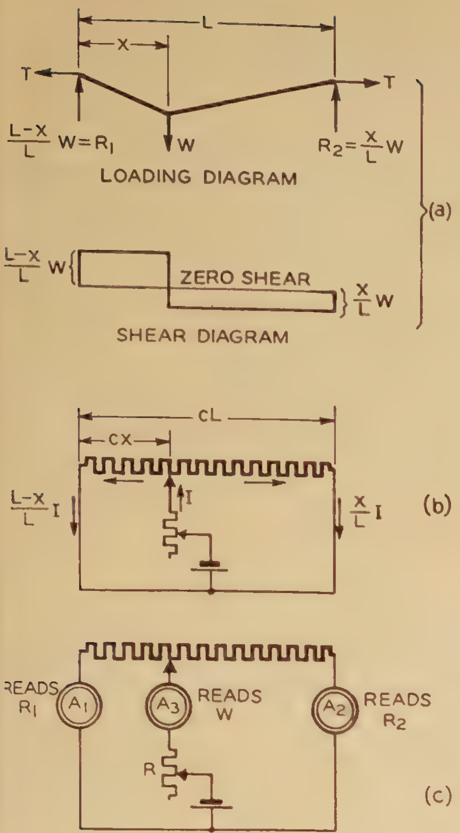

Figure 2. Elementary analogy between a loaded cable and the simple electrical circuit shown

materially affect the proper division of current and would not be readily apparent, it was decided to incorporate the span length factor into the voltmeter multiplier circuit.

Operation and Results

A systematic method of operating the computer was developed. Standard data forms were printed and given to the men laying out the catenary design. This form was provided with a tabular arrangement for listing in order: (1) the value and direction (up or down) of the messenger loads, starting from the left support; (2) the respective distances of these loads from the left support in per cent of the total span; (3) the total load carried by the messenger; and (4) the ratio of tension to span length. For use of the computing-machine operator, space was provided for listing: (1) the sag at each load point, and (2) and (3) the reactions R_1 and R_2. A separate sheet was used for each span and labeled with the numbers assigned

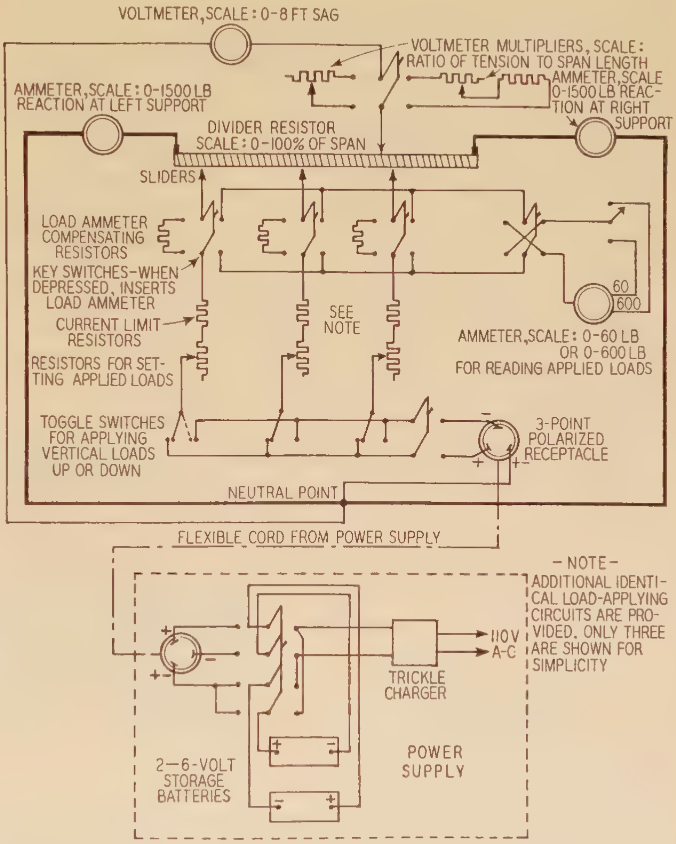

Figure 3. Wiring diagram for the computer as built, showing the added arrangements for ease in operation

design was evolved from the usual balance of one against the other. A special effort was made to locate controls and meters so as to give a visual picture of the loaded messenger, for ease in manipulation.

The main problem was to secure extremely sensitive meters. The voltmeter must have unusually high resistance because its current requirement acts as a "load" on the divider. Any resistance in the reaction ammeters causes, in effect, an extension of the length of the divider resistance. The divider scale is extended beyond the actual ends of the divider to eliminate any such error, but any appreciable extension of this scale would result in a "blind spot" for the application of "loads" that are close to the messenger supports. Also the load current and divider resistance had to be kept as low as possible to avoid heating and to keep the size of the computer within reasonable bounds. Special meters having cobalt steel magnets to give very high sensitivity were needed to obtain close accuracy in the solution of this problem.

As shown in figure 3, sliding contacts were used for applying the "load" currents to the divider. Although in general sliding connections are not satisfactory for good contact, it should be noted that, because of the inherent features of the circuit, no error is produced if the contact resistance varies slightly from day to day as the correct current still is supplied by the "load" circuit since it is read directly on the ammeter.

It should be noted also that, although the computer could be designed so that the divider scale is calibrated directly in feet of span, this would require that the connection to one end of the divider be a sliding connection. As any change in contact resistance of this slider would

to the particular messenger and structures involved. At various times, these sheets were collected from all the designers and given to the computing machine operator. He then set up the problems on the machine and completed the data sheets from the meter readings. The completed sheets were returned to the designers and the data used to calculate hangers.

The computing-machine operator's procedure, for a

given span, is as follows (see figures 3 and 4): With the data sheet as a guide, the operator sets the load sliders, in order from left to right at their given percentage locations on the divider scale. Then the toggle switches for the directions of the various loads are set, starting from left to right, from the data sheet (the loads are usually downward). The extreme left load ammeter key then is depressed, inserting the load ammeter in the extreme left slider circuit, and the corresponding load regulating resistor is adjusted until the load ammeter reads the given messenger load nearest the left support. The load ammeter key then is released and returns to its normal position, leaving the first load set and the ammeter available for setting the next load. The load is set for the next slider location in the same way, and the procedure is repeated for all the required load circuits. The divider now is completely "loaded."

Without further manipulation, the reactions may be read, immediately, on their respective meters and noted on the data sheet. The 2 reactions as read on the meters are added, and their sum should exactly equal the total messenger load given on the data sheet. This is practical proof that no mistake has been made in setting the various loads. Although it is possible that compensating errors may give the same result, the chance of such errors is so remote that results may be considered entirely satisfactory.

Without changing the load setup, the next step is to set the voltmeter multiplier scale on the tension-to-span ratio given on the data sheet. Then the sags, which determine the shape of the messenger, are read directly (in feet) from the sag voltmeter by successively moving its slider to the load locations on the divider scale. The sag at any other point in the span may be read by moving the voltmeter slider to the corresponding point on the divider scale. The controls then are brought to zero, and the computer is ready for another problem.

The computer requires very little intelligence to operate and no mechanical or electrical knowledge. It is practically foolproof, and the operator can use it continuously for long periods without going "stale" as he may with continuous mathematical calculations.

Results obtained with the computer have been very satisfactory. Accuracy has been of the order of $^1/_4$ per cent, which is equal or better than that obtained by slide rule.

The most important gain has been in saving time. A careful check has shown that the computations for a span are completed in an average time of 5 minutes on the computer and are self-checking; the same computation, done "by hand" requires approximately 40 minutes including checking time by a higher-salaried designer. One computer and one operator can handle these computations for a large squad of designers.

Other Problems Can Be Solved

The most common practice at present is to use stranded cables between guyed columns as supporting structures for the catenary, instead of beams or trusses. The only difference between the solution for the shape of these messengers and the longitudinal messengers, is that the former is designed for constant sag for different spans rather than constant tension. The shape of these cross-span messengers also is solved on this computer as built, with only a slightly different manipulation of the tension-to-span ratio multiplier.

Many other mechanical problems may be solved on slightly different computers involving essentially the same circuit and analogy. It illustrates one more surprisingly exact analogy between electrical and mechanical laws.

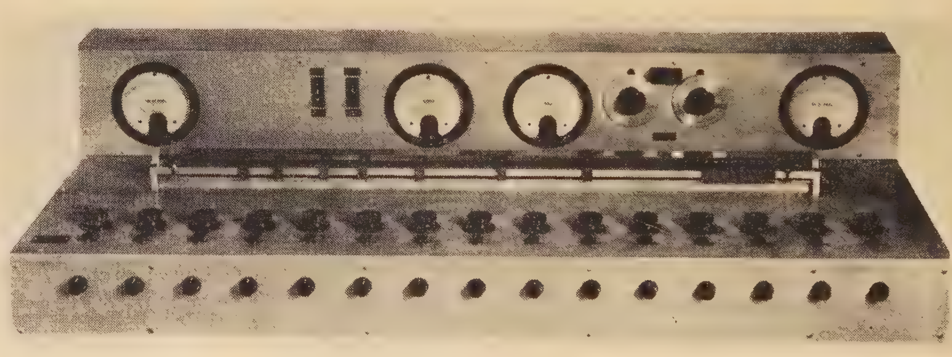

Figure 4 (above). Front and top view of the computer as built, showing compactness and logical location of apparatus for ease in visualizing problem

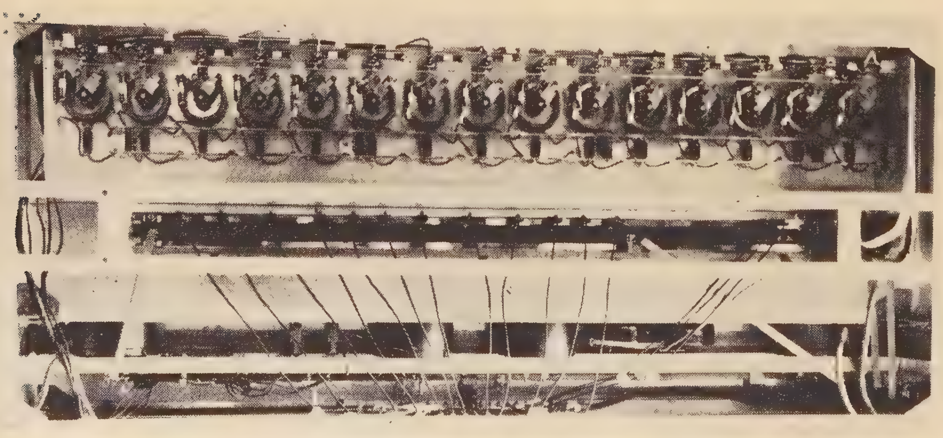

Figure 5 (left). Bottom view of finished computer, showing compact arrangement of wiring and equipment

Report of the Board of Directors

THE BOARD OF DIRECTORS of the American Institute of Electrical Engineers presents herewith to the membership its fifty-third annual report, for the fiscal year ending April 30, 1937. A general balance sheet showing the condition of the Institute's finances on April 30, 1937, together with other detailed financial statements, is included herein. This report contains a brief summary of the principal activities of the Institute during the year, more detailed information having been published from month to month in ELECTRICAL ENGINEERING.

Board of Directors' Meetings

During the year, the board of directors held 5 meetings, 4 in New York City, and 1 at Pasadena, Calif. The executive committee meetings in December and March were held in place of regular meetings of the board. Information regarding many of the more important activities of the Institute which have been under consideration by the board of directors and the committees is published each month in the section of ELECTRICAL ENGINEERING devoted to "News of Institute and Related Activities."

President's Visits

President MacCutcheon attended the winter convention and the South West District meeting. He also visited many Sections, and a considerable number of educational institutions in their vicinities. In several cases, he addressed assemblies of engineering students, while in other cases he spoke at meetings of the AIEE Student Branches.

The places visited are listed below:

Alabama
Alabama Section, Birmingham
Alabama Polytechnic Institute, Auburn
University of Alabama, Tuscaloosa

California
Los Angeles Section
San Francisco Section
University of California, Berkeley

Colorado
Denver Section
University of Colorado, Boulder

Connecticut
Connecticut Section and Yale University, New Haven

District of Columbia
American Engineering Council, Washington

Florida
Florida Section, Jacksonville, Gainesville, and Miami
University of Florida, Gainesville

Georgia
Atlanta Section
Georgia School of Technology, Atlanta

Idaho
University of Idaho, Moscow

Illinois
Chicago Section

Maryland
Baltimore Section and student convention

Massachusetts
Boston Section
Lynn Section
Springfield Section
Worcester Section
Worcester Polytechnic Institute, Worcester

Michigan
Detroit-Ann Arbor Section

Minnesota
Minnesota Section, Minneapolis

Missouri
Kansas City Section
St. Louis Section

Montana
Montana Section
Montana State College, Bozeman

New York
New York Section
Winter Convention, New York City
Board of Directors Meetings, etc.

North Carolina
North Carolina Section, Raleigh
Duke University, Durham
North Carolina State College, Raleigh

Ohio
Akron Section
Columbus Section

Oklahoma
Oklahoma City Section

Oregon
Portland Section

Pennsylvania
Erie Section
Philadelphia Section
Pittsburgh Section
Sharon Section

Rhode Island
Providence Section and Brown University

South Carolina
Columbia
Clemson Agricultural College, Clemson

South Dakota
District No. 6 Conference on Student Activities, Brookings

Tennessee
East Tennessee Section, Knoxville and Chattanooga

Texas
South West District meeting, Dallas
Houston Section and Rice Institute

Utah
Utah Section, Salt Lake City
University of Utah

Virginia
Virginia Section, Richmond

Washington
Seattle Section
Spokane Section
State College of Washington, Pullman

Wisconsin
Madison and Milwaukee Sections in Milwaukee
Summer convention committee, Milwaukee

Canada
Toronto (Ont.) Section
Vancouver (B. C.) Section

During May and June, President MacCutcheon will visit the Cincinnati, Ithaca, Lehigh Valley, Cleveland, and Rochester Sections, and Massachusetts Institute of Technology Branch, and will attend the North Eastern District meeting, Buffalo, N. Y., and the summer convention, Milwaukee, Wis.

National Conventions

Two national conventions were held during the year, and a brief report on each follows:

Summer Convention. The fifty-second summer convention was held at Pasadena, Calif., June 22–26, 1936, combined with the twenty-fourth Pacific Coast convention. Forty-two technical papers were presented at 9 sessions, and 10 student papers at 2 additional sessions. Six technical conferences were held. Other parts of the convention were the annual business meeting of the Institute, conference of officers, delegates, and members, an address by Doctor R. A. Millikan, golf and tennis tournaments, president's reception and dance, banquet, and ladies' events. The Lamme Medal for 1935 was presented to Doctor Vannevar Bush, of Cambridge, Mass. The registration was 715.

Annual Meeting. The annual business meeting of the Institute was held on Monday morning June 22, as part of the opening session of the summer convention. The annual report of the board of directors for the fiscal year ending April 30, 1936, was presented in abstract, the committee of tellers reported upon the election of officers for the administrative year beginning August 1, 1936, and a financial report was presented by National Treasurer W. I. Slichter. President-Elect MacCutcheon responded to the announcement of his election with a brief address.

Winter Convention. The twenty-fifth winter convention, held in New York City, January 25–29, 1937, was

opened by a brief general session including an address of welcome by C. R. Beardsley, chairman of the winter convention committee, an address by President MacCutcheon, and a brief announcement regarding the technical sessions by H. S. Osborne, chairman of the technical program committee. President MacCutcheon announced the award of the Alfred Noble Prize for 1936 to Abe Tilles, instructor in electrical engineering at the University of California. During the 13 sessions held, 56 papers were presented. At an evening session, the Edison Medal was presented to Doctor Alex Dow, and John C. Parker, vice-president, Consolidated Edison Company of New York, Inc., gave a lecture on "Power and People." Numerous inspection trips aroused keen interest. The registration was 1,165.

District Meetings

Two District meetings were held during the year and brief reports follow.

North Eastern District Meeting. Held in New Haven, Conn., May 6–9, 1936, with a registration of more than 300 members, students, and guests. The program consisted of 11 technical papers, 4 special addresses, 9 student papers, inspection trips, and entertainment events.

South West District Meeting. The sixth South West District meeting was held in Dallas, Texas, October 26–28, 1936. Thirteen technical papers and several special addresses were presented at 5 technical sessions, and 9 student papers at 2 student sessions. A special address was given by Doctor Matthew Luckiesh at a luncheon meeting held jointly with the Dallas Electric Club. There were also numerous inspection trips and entertainment events. The total registration was 533, including 179 students.

Sections

The activities of the Sections during the past year were outstanding in several respects, particularly with respect to the unusually large total number of meetings held, and the extensive efforts to determine and arrange for meetings of types of special interest to the members.

Seven or more meetings were held by each of 46 Sections, and only 4 Sections held fewer than 4 meetings. There was a great increase in interest in technical groups, special technical meetings, technical lectures, technical committees, discussion groups, and other arrangements desired by Section members. Twenty Sections conducted meetings of these special types in addition to the regular Section meetings. Six Sections offered courses of instruction on engineering subjects. Several Sections held local group meetings at points distant from regular meeting places.

Interest of the Sections in student activities was shown by the holding of the usual joint meetings with Branches, the sponsoring of student conventions, etc.

The East Tennessee Section was organized on September 2, 1936, under authority granted by the board of directors on May 25, 1936, including as its territory approximately the eastern half of the state. Dinner meetings were held in Knoxville and Chattanooga on September 18 and 19, respectively, with excellent attendance and much enthusiasm.

The final report of the special committee to revise Section territories, appointed by action of the board of directors in 1935 to develop plans for extending Section territories and the formation of new Sections to include in so far as practicable all parts of the United States, was presented at the meeting of the board of directors held on January 27, 1937, and the actions recommended were approved, the changes in territories to become effective August 1, 1937. The changes will bring within Section territories nearly one-half of the few hundred members now outside.

Detailed information on these activities may be found in the annual report on Section and Branch activities in the June issue of ELECTRICAL ENGINEERING, pages 762–5.

Student Activities

Under authority granted by the board of directors at its meeting held on January 26, 1937, the Columbia University Branch was organized on February 19, and the Tulane University Branch was organized on March 1, bringing the total number to 119.

The total number of meetings reported exceeds that for any previous year, and the total number of talks by students is practically equal to the largest number previously reported. However, a considerable number of Branches reported less than a normal number of meetings and no talks by students.

Students have shown an increasing interest in the opportunities to take active parts in the technical programs of national conventions and District meetings. One student technical session was included as part of the North Eastern District meeting in New Haven, 2 such sessions were held during the combined summer and Pacific Coast conventions in Pasadena, and 2 such sessions were held as parts of the South West District meeting in Dallas. The quality of the content and the presentation of the student papers inspired many favorable comments by Institute members.

The terms of enrollment of 1,253 students expired on April 30, 1937, and 674, or about 54 per cent, applied for admission as Associates. The percentage during the past few years has been approximately 50.

Table I. Section and Branch Statistics

	For Fiscal Year Ending			
	April 30, 1931	April 30, 1933	April 30, 1935	April 30, 1937
Sections				
Number of Sections	59	60	61	62
Number of Section meetings held	491	498	521	621
Total attendance	108,523	73,806	73,381	74,950
Branches				
Number of Branches	109	111	117	119
Number of Branch meetings held	1,137	1,026	986	1,363
Total attendance	51,807	59,439	36,629	46,121

More detailed information on these activities appears in the annual report on Section and Branch activities in the June issue of ELECTRICAL ENGINEERING, pages 762–5.

Section and Branch Statistics

Data on the Sections and Branches are given in table I.

Technical Program Committee

The work of the technical program committee may be considered under 3 general topics: arranging for technical programs under the present established procedures; studying alternative arrangements as to program building and publication of papers to determine whether any constructive recommendations can be made; and in co-operation with other committees making arrangements for general meetings at Institute conventions.

ARRANGEMENTS FOR TECHNICAL SESSIONS

Under the present unified publication policy, all papers for national conventions (except special addresses) and all approved discussions are published in ELECTRICAL ENGINEERING. The space allotted to the technical program committee for the current year (1,115 pages) is approximately $^2/_3$ the space used by the committee 6 years ago. Under these conditions it is naturally impossible to meet all of the desires of the technical committees for sessions and for presentation of papers. For the summer convention, 18 technical sessions were proposed, 10 scheduled, and 8 postponed or rejected. Twenty-eight per cent of the papers submitted are rejected or withdrawn because of abbreviation or other modifications required for acceptance. Other papers, the number of which, of course, is not known, are not offered to the Institute because of these conditions.

During the past 12 months, there have been 2 national conventions (the summer convention and Pacific Coast convention being consolidated into one) and 2 District meetings. At these 4 meetings, 122 papers have been presented. Every effort has been made by the technical program committee to have the meetings at the national conventions and, in co-operation with the District committees, the District meetings as well, cover the wide range of interests of the Institute membership. In general, the papers have been of high grade, upholding the tradition of the Institute as to the high quality of the material presented at its meetings. The committee has continued to encourage the conference type of session at which papers and discussions are presented without publication. Ten such conference sessions were held during the 2 national conventions.

ALTERNATIVE ARRANGEMENTS FOR TECHNICAL PROGRAMS

The field of Institute activities, namely, "the advancement of the theory and practice of electrical engineering and of the allied arts and sciences" is diverse and rapidly expanding. In spite of the very considerable provision made by the Institute for the publication and presentation of papers, it is natural that the programs should still be possible of improvement. Some members of the Institute feel that more time and space should be given in Institute programs to subjects of broad general interest including questions in which engineering and social science are jointly involved. On the other hand, many members would like more opportunity for a discussion at Institute meetings of specialized technical subjects on the frontier of immediate technological advance.

It may be questioned whether a mere extension of the program with present procedures as to publication and presentation is the best way to take care of this constant trend toward expansion. Furthermore, the unified publication policy which has served the Institute admirably during the period of depression has certain disadvantages both from the standpoint of program making and of publication. It requires relatively long intervals between the preparation and presentation of papers and involves the distribution in printed form to all members of the Institute of all technical papers, many of which are of interest to only a small proportion of the members.

With these facts in mind, the technical program committee has appointed a subcommittee which is actively studying the whole problem of procedures relating to Institute meetings. It is hoped that based upon these studies the technical program committee will, before the expiration of its term, be able to make specific recommendations for the consideration of next year's committee.

GENERAL MEETINGS

In response to may suggestions regarding the desirability of having as a part of Institute conventions meetings of broad general interest, arrangements have been made for such a meeting at the summer convention in Milwaukee. The first part of the meeting will consist of an address on the subject "The Engineer in a Changing World," by Doctor Ralph E. Flanders, who is an authoritative speaker on the relations between engineering and economic problems. The second part of the meeting will include a general discussion by the members of the Institute on the subject "How Can Institute Programs Be Made of Greatest Value to the Membership?"

Arrangements for this general session have been made by a special committee consisting of the chairmen of many of the principal committees of the Institute. Based upon the results of this meeting, the special committee will make recommendations to the board of directors regarding the advisability of having similar meetings at future Institute conventions.

Publication Committee

Throughout the year effort has been made to improve the usefulness of ELECTRICAL ENGINEERING to the membership by including more articles of a general interest type.

The initial budget included an extra appropriation specifically for this purpose, so that the publication of highly technical papers would not have to be curtailed to permit the publication of general interest articles. At the January meeting of the board of directors, a further

specific appropriation was granted to cover the publication of general interest articles.

In requesting this latter appropriation, the publication committee defined the scope of general interest articles as follows:

Timely review articles on various phases of electrical engineering, feature articles by men prominent in the Institute or in other fields of scientific and engineering endeavor, reprints of important electrical engineering papers originally published in English abroad, reprints of important papers published in this country in other fields of engineering, and appropriate general articles on economics and the status of the engineer written by outstanding men; also at times interpretive abstracts of important and highly technical papers published in full elsewhere in ELECTRICAL ENGINEERING; possibly also some English translations of important electrical engineering papers published originally in a foreign language.

Starting with the January issue ELECTRICAL ENGINEERING acquired "The Easy-Reading Page." Based on scientific studies and in the interests of reader comfort, the typography, the paper, and the ink have been selected to provide a nonglare easy-reading page. Many letters have been received commenting favorably on this change.

In general, the unified publication plan adopted by the board of directors in August 1933 has been followed.

Membership Committee

The work of the membership committee has followed along much the same lines as it has for the past 2 or 3 years. Probably the most important change has been the increased responsibility given to the District vice-chairmen of the committee in connection with the Section membership committees in each District. The vice-chairmen have done an excellent job, and together with the very good co-operation given them by the Section committees, have made possible a report that shows marked improvement in the Institute's membership analysis. The entire membership has again given the committees much assistance this year by suggesting that certain nonmembers be approached. A new pamphlet was prepared, published, and, though written for membership work mainly, it was placed in the hands of every member of the Institute. It is titled, "Membership in the American Institute of Electrical Engineers."

Table II. Membership Statistics for the Fiscal Year Ending April 30, 1937

	Honorary	Fellow	Member	6-Year Associate	Associate	Total
Membership on April 30, 1936	11	699	3,912	5,679	4,299	14,600
Additions						
Transferred	1	27	182	571		
New members qualified		6	150	40	1,285	
Former members reinstated		2	17	37	42	
	12	734	4,261	6,327	5,626	16,960
Deductions						
Died	2	19	26	32	4	
Resigned		2	34	135	91	
Transferred		1	24	165	591	
Dropped		3	59	204	260	
Membership on April 30, 1937	10	709	4,118	5,791	4,680	15,308

Table III. Number of Applications Received From Enrolled Students and From All Others

Year Ending	From Students	From All Others	Total
April 30, 1937	716	1,040	1,756
April 30, 1936	631	946	1,577
April 30, 1935	575	715	1,290
April 30, 1934	467	496	963
April 30, 1933	674	305	979

Table IV. Number of Enrolled Students

April 30, 1937	4,503 (2,249)
April 30, 1936	4,049 (1,991)
April 30, 1935	3,806 (1,983)
April 30, 1934	3,186 (1,548)
April 30, 1933	3,260 (1,494)

Following the number of Students reported for April 30 of each year is indicated within parentheses the number of new applications received during that year; the difference between this number and the reported total, of course, reflects the number of renewals of Student enrollment for the corresponding period.

Table V. Number of Members in Section Territory Reinstated

August 1, 1936, to April 30, 1937	460
Year beginning August 1, 1935	663
Year beginning August 1, 1934	831
Year beginning August 1, 1933	741
Year beginning August 1, 1932	277

Table VI. Membership of the Institute, April 30, 1937

Of the 15,308 members reported for April 30, 1937, 13,439 are fully paid to April 30, 1937. The balance of 1,869 are divided into the following groups:

1. Members owing dues to April 30, 1936.
Total number of members who have not acted upon resolution of board of directors adopted in January 1937 providing an extension of time for payment of these dues 505
2. Members owing dues to April 30, 1937 1,364
(During the period May 1 to 25, 1937, 311 members have paid dues to April 30, 1937, reducing the total to 1,053).

The changes that have occurred in the Institute's membership totals during the year are given in table II. The most interesting figures are those that give the change in total enrollment. There is shown a gain of 708 which is more than twice the gain reported a year ago, the first year of increase since the business depression. There was a good increase in the number of "new members qualified," and the decrease of the members "dropped" column is encouraging. The number dropped this year is 526 compared with 797 last year.

The number of applications received increased again, as shown in table III, by about 11 per cent. The increase of some 13 per cent in Student applications for transfer, and the increase in applications for Student membership, as well as in the total Student enrollment (see table IV) are all very encouraging.

Table V shows a steady decrease in delinquent reinstatements for the past 2 years. This is as it should be since the total number of delinquents has been reduced considerably over the past 2 years. There are 1,869 owing dues on April 30, 1937, as recorded in table VI. The same figure last year was 2,154. The figure of 460

Table VII. Memberships Fully Paid

	Membership as of April 30	Number of Members Fully Paid as of April 30	Per Cent Fully Paid
1937	15,308	13,439	87.8
1936	14,600	12,446	85.2
1935	14,269	11,512	80.5
1927 (year of maximum membership)	18,344	16,247	88.5

Table VIII. Record of AIEE Membership

	Total Membership May 1		Total Membership May 1		Total Membership May 1		Total Membership May 1
1884	71	1899	1,133	1913	7,654	1927	18,344
1885	209	1900	1,183	1914	7,876	1928	18,265
1886	250	1901	1,260	1915	8,054	1929	18,133
1887	314	1902	1,549	1916	8,202	1930	18,003
1889	333	1903	2,229	1917	8,710	1931	18,334
1890	427	1904	3,027	1918	9,282	1932	17,550
1891	541	1905	3,460	1919	10,352	1933	17,019
1892	615	1906	3,870	1920	11,345	1934	15,200
1893	673	1907	4,521	1921	13,215	1935	14,269
1894	800	1908	5,674	1922	14,263	1936	14,600
1895	944	1909	6,400	1923	15,298	1937	15,308
1896	1,035	1910	6,681	1924	16,455		
1897	1,073	1911	7,117	1925	17,319		
1898	1,098	1912	7,459	1926	18,158		

in table V is not directly comparable with the others since it represents only a 9-month period, but the same figure for the same period last year was 608, which indicates a definite trend.

Table VII shows the percentage of fully paid membership to be within less than 1 per cent of the highest figure ever recorded. An increase of 2.6 per cent over last year should give additional encouragement to the members.

Table VIII gives an interesting record of the Institute's growth since its founding in 1884.

Deaths

The following deaths occurred during the year:

Honorary Members: Elihu Thomson, Edward Weston.

Fellows: James R. C. Armstrong, Charles L. Fortescue, William D. Gherky, Stephen Q. Hayes, Halbert P. Hill, William B. Jackson, Samuel M. Kintner, Frank A. Laws, Edward B. Meyer, D. McFarlan Moore, George R. Murphy, Louis C. Nichols, Louis F. Reinhard, Albert S. Richey, Robert A. Ross, Frederick A. Scheffler, George C. Shaad, Arthur Williams, Fremont Wilson.

Members: Clinton J. Axtell, Allan Cunningham, Frederick S. Cutting, William A. E. Doying, Albert G. T. Goodwin, William K. Hale, Charles E. Hebbert, William A. Hillebrand, Joseph D. Israel, Hamilton McR. Jones, Philip A. Lang, Adolf J. Lobeck, Meldon H. Merrill, Elam Miller, Henry A. Morss, Robert E. Orr, Hugh Pattison, Albert T. Perkins, Arthur J. Ralph, Crandall Z. Rosencrans, Lester R. Sailer, John A. Sirnit, Guy S. Turner, William S. Twining, William F. White, Russell A. Yerxa.

Associates: Eugene L. Alexander, Alfred Alsaker, James D. Andrew, Walter E. Bare, Frederick H. Barrington, Irving F. Day, Burton L. Delack, William H. Dieringer, John C. Dolph, Francis E. Donohoe, William G. Ely, Paul Engleheart, William H. R. Fraser, Harry W. Fuller, Nicholas S. Hill, John Jenkinson, Ed. C. Jerman, David H. Kelly, Edgar Knowlton, Edward F. Lawton, Robert Lundell, Frank G. McRae, Julius Meyer, Jesse B. Millard, Thomas E. Penard, John W. Purcell, John A. Rockwood, A. W. Russell, Charles J. Russell, Thomas Spencer, Harry B. Thayer, Carroll Thomas, Earle Lamar Tyler, Hugo Vecera, Francis R. Welles, Charles V. Woodward.

Board of Examiners

The board of examiners held 10 meetings during the past year, averaging about 2½ hours each, and considered 3,787 cases, divided as shown in table IX.

Standards Committee

The activities of the standards committee for the past year reflect the general upturn in the engineering field with increased interest in standardization activities. The AIEE committees, as well as the sectional committees under the American Standards Association, have been extremely active. Much of this activity has had to do with needed revisions and suggested further development of existing standards.

For instance, the AIEE committee on applications to marine work is preparing an extensive revision of Standard No. 45, "Recommended Practise for Electrical Installations on Shipboard" (Marine Rules). These rules have been in general use without change since 1930. The committee on protective devices submitted to the standards committee 2 reports, one dealing with a proposed revision of "Oil Circuit Breaker Standards," No. 19, now before a sectional committee working under ASA procedure, and the other a new project, "Fuses Above 600 Volts." Both were ordered printed and circulated in report form.

The AIEE committee on instruments and measurements presented a report giving latest revised data on sphere-gap spark-over voltages. This was published by order of the standards committee in ELECTRICAL ENGINEERING so that it might become generally available. Eventually, these data will be included in a general revision, now being developed by the same committee, of Standard No. 4, "Measurement of Test Voltages in Dielectric Tests."

Renewed activities in the development of the test code

Table IX. Applications for Admission and Transfer

Applications for Admission		
Recommended for grade of Associate	1,077	
Re-elected to the grade of Associate	112	
Not recommended	3	1,192
Recommended for grade of Member	113	
Re-elected to the grade of Member	20	
Not recommended	38	171
Recommended for grade of Fellow	3	
Re-elected to the grade of Fellow	1	
Not recommended		4
Applications for Transfer		
Recommended for grade of Member	167	
Not recommended	27	194
Recommended for grade of Fellow	24	
Not recommended	2	26
Students		
Recommended for enrollment as Students		2,200
Total		3,787

series have also taken place during the past year. An informal session was held during last winter's convention for the discussion of the codes. As a result a revised edition of both the synchronous and the induction machines codes will be issued, and a new code added to the series on d-c machines. The standards committee delegated to the committee on instruments and measurements the development of a code for measurements. Likewise the subcommittee on sound has offered for approval a "Code for Apparatus Noise Measurement."

Many of the ASA sectional committees on which the Institute has representation have been similarly increasingly active. The sectional committee on transformers is about to issue a very complete report on transformers. This will embody not only the revised and enlarged standards themselves, but will include as appendices, the test code and guides for operation of transformers. The sectional committee covering graphical symbols, letter symbols, and abbreviations, has been completely reorganized and is now revising the standards developed by its predecessor. The sectional committee on insulated wires and cables is about ready to issue a series of both revised standards and new ones. These represent only a few of the active sectional committees.

The Institute's co-operation through the standards committee was sought in several general fields. An appointment was made of a representative on a research committee on grounding to study the whole situation. Representation was also had on a committee on radio-electrical co-ordination, a field whose scope and possibilities will require much careful co-operative study and co-ordination work. The most recent development was the committee on international standardization of photometric units to which appointment was made on invitation of the National Bureau of Standards.

It might be well to point out in closing that there seems to be a general tendency under ASA procedure for sectional committees to issue reports in which are combined not only standards, but much related material. This is of particular interest from a historical viewpoint. When development was proposed by the Institute of codes and operating recommendations in particular much opposition was incurred and argument offered opposing such activity. Finally, approval was obtained on the basis that such reports when issued must be entirely distinct from the accepted standards. Evidently, a better understanding of the subject matter has eliminated opposition to such projects.

U.S. National Committee of the IEC

The past year has been an active one for the International Electrotechnical Commission for a year in which no plenary meeting has been held. The commission has been saddened by the deaths of two of its honorary presidents, Professor Elihu Thomson and Professor Paul Janet of France. The loss sustained by these 2 deaths will not be easily forgotten.

Meetings of advisory committees as follows were held during the year: storage batteries—number 21, aluminum—number 7, radio communication—number 12, electrical installations on shipboard—number 18, and international electrotechnical vocabulary—number 1. In addition, the international special committee on radio interference held a meeting.

President Burke has continued to devote his attention to the financial affairs of the commission, so that the commission ended its fiscal year on January 1 in the most favorable financial position which it has enjoyed for a number of years.

Meetings of the following advisory committees will be held in Paris June 17–23, 1937:

Rating of electrical machinery, transformer section only—number 2

Standard voltages and currents and high voltage insulators—number 8

Electric traction equipment—number 9

Electrical measuring instruments—number 13

It is expected that the U.S. national committee will be represented at these meetings by a good delegation, which will be headed by President Sharp. In addition, there will be held in Paris, June 30 to July 3, an international conference on acoustics. The purpose of this meeting will be to make plans as to the handling of a comprehensive program of standardization in the acoustic field. The conference will be held under the auspices of the IEC, but it is not yet certain as to how the international acoustical work will be set up. The work originally was proposed to the IEC by the international consultative committee on telephony (CCIF), and it is now contemplated that the work will include definitions, units, notations, graphical symbols, methods of measurement and measuring apparatus, including noise meters, electrotechnical acoustics, recording transmission and reproduction of sound (except telephony), architectural acoustics, noise abatement, etc. Acoustical work in the United States is well advanced, 3 important standards in the field having been approved as American standards. The sectional committee in charge of the work is a most authoritative and representative body. The U.S. national committee is accordingly in an excellent position to take care of this work on behalf of American industry. The U.S. national committee will be represented at the meetings by President Sharp, Doctor Harvey Fletcher, and probably others.

The following reports of progress in specific technical projects will be of interest:

International Electrotechnical Vocabulary—Number 1

This work was undertaken by the IEC soon after its formation in 1904. It has now progressed to the point where it is planned to publish the first edition during 1937. The vocabulary will contain over 2,000 scientific and industrial terms used in the various branches of electrotechnics. The terms are given in both English and French, and translations of the title are given in German, Italian, Spanish, and Esperanto.

The whole work is divided into 14 sections, the first of which covers fundamental and general definitions. The others more specifically deal with: machines and transformers; switchgear and control gear; apparatus for scientific and industrial measurements; generation, transmission, distribution; electrical traction; power applications; thermic applications; lighting; electrochemistry; telegraphy, telephony; radiology; electrobiology.

While the committee developing this "International Vocabulary" appreciates that it does not constitute a complete unification of electrotechnical nomenclature, it believes that through periodic review and revision based on the constructive criticism of electricians of the world, it should become increasingly valuable to engineers.

As the edition will be limited, copies should be reserved at once by writing to the U.S. national committee of the International Electrotechnical Commission at 29 West 39th Street, New York. The price of the "Vocabulary" will be about $2.50.

Steam Turbines—Number 5

The secretariat for this project is held by the U.S. national committee, and during the year they prepared an appendix to IEC Publication No. 46, "Rules for Acceptance Tests for Steam Turbines—Supplementary Notes to Section 4, Instruments and Methods of Measurement," which was sent to the central office during the year for circulation for final approval under the 6-months rule. Active work is now going forward on expanding the rules to cover non-condensing back pressure extraction and mixed pressure turbines.

Insulating Oils—Number 10

The U.S. national committee appointed a representative on an international subcommittee to draw up an ideal testing procedure for determining the sludging properties of insulating oil. This work is going forward.

Terminal Markings—Number 16

During the year the American standard on rotation, connections and terminal markings for electric power apparatus was approved and printed. This document has been transmitted to the central office to become the American part of the international specifications for terminal markings.

Switchgear—Number 17

During the year the draft IEC specification for a-c circuit breakers was studied by the U.S. national committee, and approved for service as an international standard. It is expected that the revised edition will be published shortly. During the year IEC Publication No. 54 ("IEC recommendations for standard direction of motion of operating devices and for indicating lamps for circuit breakers") appeared in printed form.

Electric Cables—Number 20

During the year IEC specifications for tests on impregnated-paper-insulated lead-covered cables having voltages from 10 kv to 66 kv were considered and discussed. The U.S. national committee had technical objections to these rules, and voted against their issuance. However, these objections were withdrawn with the understanding that an immediate revision of the rules would be undertaken.

The next plenary meeting of the International Electrotechnical Commission is scheduled to be held in England, June 1938.

Committee on Safety Codes

The committee submitted proposals for expanding the scope of its activities in order that it might study technical and engineering problems in connection with the safer use of electricity. The present by-laws limit the committee to matters connected with safety codes which for years have been handled by other organizations. After consideration by the Institute policy committee and the board, no formal action was taken on the proposal for enlarged scope. However, the board is interested in the possibility that the Institute within its proper scope may make further contributions to the cause of safety and has invited the committee on safety codes to make further suggestions to this end. The committee is preparing to comply with the board's invitation in the immediate future.

The chairman of the committee on safety codes, as the AIEE representative, attended the annual meeting of the electrical committee of the National Fire Protection Association. At this meeting the biennial revision of the national electrical code was made.

The chairman represents the Institute on the committee on low voltage hazards of the National Safety Council but was called upon for no action during the past year.

The chairman attended the annual meeting of the National Fire Waste Council in Washington. Little of electrical engineering interest is considered at these meetings.

Co-ordination Committee

The committee followed the established practice of requesting District and Section officers to submit by January 1 applications for the authorization of any national conventions and District meetings desired in their respective Districts during the calendar year 1938, and a recommended schedule of such meetings has been presented to the board of directors and approved.

Institute Policy Committee

The Institute policy committee has considered and reported upon 2 broad questions referred to it by the board of directors.

The first of these was the question of the possible enlargement of the scope of the committee on safety codes. A report was submitted to the board of directors generally endorsing the proposal and suggesting a review with specific suggestions from the committee itself.

The committee has also reported to the board of directors on the recommendation of the committee on research that the Institute contribute financially to the support of such researches as the Institute may recommend, under its sponsorship, to the Engineering Foundation. An extensive study was made of this question, and a report was submitted to the board of directors indicating a divided opinion within the committee, and the consequent inability to make a recommendation either for or against the proposal.

Two resolutions submitted to the board of directors, one proposing the establishment of the office of executive vice-president, and the other proposing an additional man, for further development of the work of the Institute committees, to be added to the staff of the national secretary, have been referred to this committee and are now under examination.

Special Committee to Consider Dues of Associates and Related Matters

A final report of this committee was presented to the board of directors recommending no changes in the present

rules and dues. This was received and approved and the committee discharged.

Committee on Code of Principles of Professional Conduct

During the year a number of points were raised by non-members of the committee and these points were presented by letter to the committee members. In no case has any member of the committee urged that any change be made in the present code of principles of professional conduct.

Committee on Constitution and By-Laws

This committee had no meetings, as no matters had been referred to it until in the latter part of the year, when it was requested to consider several proposed amendments to the constitution and by-laws of the Institute.

Committee on Economic Status of the Engineer

The committee has conducted a somewhat limited but pertinent study of the economic status of the engineer as it affects his ability to earn an income commensurate with his needs and his value to the welfare of mankind. This study has disclosed much information in reports made by various organizations interested in education. It is hoped a further study of these data will confirm the impression that in general engineers have "weathered" the depression pretty well.

This committee recommends activity on the part of engineers in seeking channels other than the AIEE through which they may take active part in educating the public regarding affairs of significance to our economic welfare which involve engineering works. For further information on this point, attention is called to the papers obtained by the special committee on Institute activities which will be presented and discussed at the summer convention.

Committee on Award of Institute Prizes

Five national prizes and 13 District prizes for Institute papers presented in 1935 were awarded to the authors. These awards were announced in the 1936 issues of Electrical Engineering for June and July.

The committee has made a careful study of a number of suggestions for changes in the rules for the award of Institute prizes. As a result they have recommended certain changes which have been adopted by the board of directors. These changes provide that in the future the national prize for Branch papers shall be based upon the college year, i.e., July 1 to June 30 inclusive, rather than the calendar year as at present. They also provide for a District prize for graduate student papers. A revised issue of the rules for the award of prizes including these changes is now being printed.

Committee on Award of Columbia University Scholarships

By arrangement with Columbia University, this committee of the AIEE has the privilege of awarding each year a scholarship in electrical engineering for each class, the amount covering the annual tuition fees of $380.

As a result of improving business conditions, no definite application for the scholarship for the academic year 1936–37 was received.

Edison Medal

The Edison Medal, which is awarded by a committee composed of 24 members of the Institute, was, for 1936, awarded to Doctor Alex Dow for "outstanding leadership in the development of the central station industry and its service to the public," and was presented on January 27, 1937, during the winter convention. The medal may be awarded annually "for meritorious achievement in electrical science, electrical engineering, or the electrical arts."

John Fritz Medal

The John Fritz Medal board of award, composed of representatives of the national societies of civil, mining, mechanical, and electrical engineers, awarded the thirty-third medal (for 1937) to Arthur Newell Talbot, professor emeritus of engineering, University of Illinois, who was cited as "moulder of men, eminent consultant on engineering projects, leader of research, and outstanding educator in civil engineering."

Lamme Medal

The Lamme Medal committee awarded the medal for 1936 to Doctor Frank Conrad "for his pioneering and basic developments in the fields of electric metering and protective systems." Arrangements are being made for the presentation of the medal at the annual summer convention at Milwaukee, Wis., June 21–25, 1937. The medal may be awarded annually to a member of the AIEE "who has shown meritorious achievement in the development of electrical apparatus or machinery."

Alfred Noble Prize

This prize, established in 1929, consists of a certificate and a cash award of $500 from the income from a fund contributed by engineers and others to perpetuate the name and achievements of Alfred Noble, past-president of the ASCE and of the Western Society of Engineers. It may be made to a member of any of the co-operating societies, ASCE, AIME, ASME, AIEE, or WSE, for a technical paper of particular merit accepted by the publication committee of any of these societies, provided the author, at the time of such acceptance, is not over 30 years of age. The award for 1936 was presented to Abe Tilles, instructor in electrical engineering at the University of California, Berkeley.

Washington Award

The Washington Award for 1937 was bestowed upon Doctor Frederick Gardner Cottrell, "for his social vision in dedicating to the perpetuation of research the rewards of his achievements in science and engineering," and was presented to him on February 23, 1937. This award may be made annually to an engineer by the commission of award composed of 9 representatives of the Western Society of Engineers and 2 each of the American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers, American Society of Mechanical Engineers, and AIEE.

Iwadare Foundation Committee

The fifth lecturer to visit Japan was Doctor Edwin H. Colpitts, who has just retired from his position as executive vice-president of Bell Telephone Laboratories, Inc. Doctor Colpitts sailed from San Francisco on March 4 last and planned to be in Japan throughout the month of April. He gave 3 different lectures: "Organized Scientific Research in Bell Telephone Laboratories," "Recent Trends in Toll Transmission in the United States," and "Scientific Research Applied to the Telephone Transmitter and Receiver."

Employment Service

The Institute co-operates with the national societies of civil, mining, and mechanical engineers in operation of the Engineering Societies Employment Service with its main office in the Engineering Societies Building, New York. Offices are operated in Chicago and San Francisco also. In addition to the societies named, others co-operate in certain of the offices as follows: New York—Society of Naval Architects and Marine Engineers; Chicago—Western Society of Engineers; San Francisco—California Section of the American Chemical Society; and the Engineers' Club of San Francisco.

The service is supported by the joint contributions of the societies and their individual members who are benefited. In addition to the publication of the employment service announcements monthly in ELECTRICAL ENGINEERING, weekly subscription bulletins are issued for those seeking positions.

An analysis of this employment service as reported to the national societies is given in table X.

American Engineering Council

The American Engineering Council has continued its activities in the wide range of affairs which are found within the scope of its objectives: "to further the public welfare wherever technical and engineering knowledge and experience are involved, and to consider and act upon matters of common concern to the engineering and allied technical professions," and within the interests of its many member-bodies.

The work of Council has, during the past year, been carried on by 4 groups of committees:

1. Public affairs
2. Engineering-economics
3. United action of member organizations
4. AEC operating

Some of the principal actions taken by the assembly at its annual meeting held January 15 and 16, 1937, provide for:

1. Efforts to encourage the completion of the basic mapping program of the United States.
2. Continued support of efforts which will bring about ultimate unification of engineering in public works activities.
3. Support of the proposed plan for a single court of patent appeals, and opposition to the various proposals which would restrict the freedom of owners of patents.
4. Initiative to be taken by Council in the formation of co-operative relations between its staff and committees and representative groups in economics and social science to enable the engineering profession to make its proper contributions to the consideration and solution of problems in these broader fields.
5. Study by the executive committee of the possibility of developing and carrying out a broad educational program to encourage rural electrification.

A conference of secretaries of engineering societies was held under the sponsorship of Council on January 14, and was attended by secretaries of about 30 national, state, and local organizations.

A committee of Council has continued to confer with representatives of the Bureau of Labor Statistics regarding the contents of the report upon the 1935 survey of the engineering profession. Three articles have been published. A detailed report of the survey will be published later by the bureau.

Council appointed an advisory committee to co-operate with the Lewis Historical Publishing Company in connection with preparations for a new edition of "Who's Who in Engineering."

More detailed information regarding the work of Council has been published frequently in ELECTRICAL ENGINEERING.

Table X. Analysis of Employment Service

	Men Registered				Men Placed			
Month	New York	Chicago	San Francisco	Total	New York	Chicago	San Francisco	Total
1936								
May	186	61	71	318	46	31	32	109
June	228	113	73	414	48	23	22	93
July	154	60	66	280	47	41	35	123
August	114	35	58	207	51	39	33	123
September	125	82	57	264	60	36	26	122
October	125	49	67	241	51	30	27	108
November	128	37	39	204	57	36	27	120
December	115	65	44	224	64	36	24	124
1937								
January	197	48	69	314	72	36	32	140
February	282	83	62	427	50	36	26	112
March	346	107	109	562	65	33	41	139
April	475	94	78	647	54	40	25	119
Total	2,475	834	793	4,102	665	417	350	1,432

United Engineering Trustees, Inc.

This organization, as an agency of the founder societies, made further improvements in the Engineering Societies Building, including the redecoration of the rooms occupied by the library and improvements in elevator equipment and service, and presented a plan for resuming payments to the depreciation and renewal fund of the building. Much consideration has been given to investment problems in order to secure the maximum income consistent with safety of principal.

The UET continued as treasurer of the Engineers' Council for Professional Development.

An abstract of the annual report of the United Engineering Trustees, Inc., was published in ELECTRICAL ENGINEERING for December, 1936, pages 1400–01.

Engineering Foundation

The Engineering Foundation suffered a serious loss in the death of its director, Doctor Alfred D. Flinn, on March 14, 1937.

During 1936, the Foundation supplied financial support for many research projects sponsored by the founder societies, notably the following: ASCE—earths and foundations; AIME—alloys of iron and barodynamic studies; ASME—cottonseed processing, cutting fluids, critical pressure steam boilers, fluid meters, boiler feed water, strength of gear teeth, "Cutting of Metals" handbook; AIEE—welding with pure iron electrodes (terminated on September 30, 1936) and comprehensive program under supervision of the welding research committee sponsored by the AIEE and the American Welding Society, with the co-operation of industries.

The Foundation also assisted in studies of the plastic flow of concrete at the University of California, and the plasticity of metals at the University of Pittsburgh.

It continued to assist the Engineers' Council for Professional Development and the Personnel Research Federation.

An abstract of the annual report of the Engineering Foundation was published in the December 1936 issue of ELECTRICAL ENGINEERING, pages 1401–02.

Engineering Societies Library

The Engineering Societies Library, which was formed by combining the separate libraries of the 4 national societies of civil, mining and metallurgical, mechanical, and electrical engineers, and the preparation of a composite card catalog, has been expanded as a single engineering library, which probably constitutes the best collection of this type of literature in the country.

On September 30, 1936, the library had 138,742 volumes, 7,246 maps, and 4,298 bibliographies. Books, pamphlets, and maps totaling 12,148 were received during the year ending at that time. Current issues of 1,358 periodicals were received. Work progressed rapidly on a classified index to periodicals, and the index now contains more than 150,000 references to articles published since 1927.

Special services rendered by the library include: photoprints, searches, abstracts, translations, bibliographies, book loans by mail, etc.

An abstract of the annual report of the library was published on page 1402 of ELECTRICAL ENGINEERING for December 1936.

Engineers' Council for Professional Development

This council, which was formally organized in 1932 for the enhancement of the professional status of the engineer, includes 3 representatives of each of the 7 participating organizations: the national societies of chemical, civil, electrical, mechanical, and mining and metallurgical engineers, the Society for the Promotion of Engineering Education, and the National Council of State Boards of Engineering Examiners.

The principal activities of ECPD include the guidance of young individuals thinking of entering the engineering field, the accrediting of engineering schools, encouragement and assistance to individuals continuing their engineering and cultural training during several years after graduation, and the establishment of suitable standards for indicating the attainment of the status of an engineer.

Actions were taken, at the annual meeting in October 1936, upon curricula of 39 institutions in regions I and II, and a list of accredited curricula in those regions was issued soon afterward. Actions upon curricula of a few additional institutions were taken on April 23, 1937. Consideration of engineering curricula throughout the remainder of the country is proceeding rapidly in preparation for actions at the annual meeting in October 1937.

The committe on professional training selected a few cities in which conditions seemed especially favorable for the establishment of operating programs for assisting junior engineers in their self-development. Excellent progress was made in Providence through the leadership of the Providence Engineering Society.

Detailed information regarding the recommendations submitted by ECPD to the participating organizations and other features of its activities were published during the year in numerous issues of ELECTRICAL ENGINEERING.

Representatives

The Institute has continued its representation upon many joint committees and national bodies, with which it co-operates in a wide range of activities of interest and importance to engineers and others.

A complete list of representatives was published in the

September 1936 issue of ELECTRICAL ENGINEERING and in the 1937 Year Book.

Finance Committee

The committee, as usual, recommended a detailed budget to the board of directors, passed upon the expenditures for various purposes, made recommendations regarding delinquent members, and performed the other duties prescribed for it in the constitution and by-laws.

Haskins and Sells, certified public accountants, have audited the books, and their report follows.

Respectfully submitted for the board of directors.

H. H. HENLINE,
National Secretary

May 24, 1937

HASKINS & SELLS
CERTIFIED PUBLIC ACCOUNTANTS

22 EAST 40TH STREET
NEW YORK

May 21, 1937

American Institute of Electrical Engineers,
33 West 39th Street,
New York.

Dear Sirs:

We have made an examination of your balance sheet as of April 30, 1937, and of your recorded cash receipts and disbursements for the year ended that date. In connection therewith, we examined or tested your accounting records and other supporting evidence in a manner and to the extent which we considered appropriate in view of your system of internal accounting control. We present the following financial statements:

Balance Sheet, April 30, 1937 (Exhibit A).
Property and Restricted Funds Securities, Less Reserve for Bonds of Doubtful Value (Schedule 1).

Statement of Recorded Cash Receipts and Disbursements of General Fund for the Year Ended April 30, 1937 (Exhibit B).

Statement of Recorded Cash Receipts and Disbursements of Property and Restricted Funds for the Year Ended April 30, 1937 (Exhibit C).

In accordance with the terms of our engagement, members and other debtors were not requested to confirm to us the amounts receivable from them at April 30, 1937, and, in accordance with the usual practice of the Institute, no provision has been made for dues which may prove to be uncollectible.

In our opinion, based upon such examination and subject to the foregoing, the accompanying Exhibit A fairly presents your financial condition at April 30, 1937, and the accompanying Exhibits B and C set forth your recorded cash receipts and your disbursements of funds, as indicated, for the year ended that date.

Yours truly,

HASKINS & SELLS

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Balance Sheet, April 30, 1937

Exhibit A

ASSETS		
Property Fund Investments:		
One-fourth interest in real estate and other assets of United Engineering Trustees, Inc., exclusive of Trust Funds	$496,948.48	
Equipment:		
Library—Volumes and fixtures	37,296.37	
Office furniture and fixtures (less reserve for depreciation, $27,386.77)	6,856.55	
Works of art, etc	3,001.35	
Securities—at cost (market quotation value, $10,556.28)—Schedule 1	10,042.53	
Cash (See Exhibit C)	22.47	
Total property fund investments		$554,167.75
Restricted Fund Investments:		
Securities—at cost, less reserve for bonds of doubtful value (market quotation value, $207,189.52)—Schedule 1	$205,306.02	
Cash (See Exhibit C)	5,977.69	
Accrued interest receivable	209.16	
Total restricted fund investments		211,492.87
Current Assets:		
Cash (See Exhibit B)	$ 51,700.32	
Accounts receivable:		
Members—For dues	17,566.57	
Advertisers	582.00	
Miscellaneous	1,790.51	
Accrued interest on investments	2,736.58	
Inventories:		
TRANSACTIONS, etc	2,244.50	
Text and cover paper	4,974.21	
Work in process (May issue of ELECTRICAL ENGINEERING)	4,046.97	
Badges	1,006.10	
Total current assets		86,647.76
Total		$852,308.38

LIABILITIES		
Property Fund Reserve		$554,167.75
Restricted Fund Reserves:		
Reserve Capital Fund	$190,708.37	
Life Membership Fund	9,873.50	
International Electrical Congress of St. Louis Library Fund	5,272.25	
Lamme Medal Fund	4,567.33	
Mailloux Fund	1,071.42	
Total restricted fund reserves		211,492.87
Current Liabilities—Accounts Payable		8,917.61
Deferred Income:		
Dues received in advance	$ 3,858.31	
Entrance fees and dues advanced by applicants for membership	684.00	
Deferred credits and other unallocated receipts	691.70	
Subscriptions for TRANSACTIONS received in advance	28.00	
Reserve for prepaid subscriptions for ELECTRICAL ENGINEERING	7,500.00	
Total deferred income		12,762.01
Surplus		64,968.14
Total		$852,308.38

Property and Restricted Funds Securities, Less Reserve for Bonds of Doubtful Value, April 30, 1937

Exhibit A, Schedule 1

	Face Value of Bonds or Number of Shares of Stock	Property Fund (Equipment Replacements)	Restricted Funds: Reserve Capital Fund	Restricted Funds: Life Membership Fund	Restricted Funds: International Electrical Congress of St. Louis Library Fund	Restricted Funds: Lamme Medal Fund	Restricted Funds: Mailloux Fund	Total
Railroad Bonds:								
Alleghany Corporation 20-year collateral trust convertible 5%, due 1949	$15,000.00		$ 10,627.50			$4,330.00		$ 14,957.50
Baltimore & Ohio Railroad Company 6% refunding and general mortage series C, due 1995	12,000.00		8,940.00					8,940.00
Central of Georgia Railway Company 5% consolidated mortgage, due 1945	3,000.00		1,477.50					1,477.50
Chicago, Burlington & Quincy Railroad Company 5% first and refunding mortgage series A, due 1971	1,000.00		1,010.00					1,010.00
Chicago & Erie Railroad Company 5% first mortgage, due 1982	1,000.00		1,105.00					1,105.00
Chicago & Northwestern Railway Company 6½%, due March 1, 1936	9,000.00		7,202.50					7,202.50
Cleveland Union Terminals Company 5% sinking fund series B, due 1973	4,000.00	$4,010.00						
Florida East Coast Railway Company 5% first and refunding mortgage series A, due 1974 (certificates of deposit)	10,000.00		9,818.75					9,818.75
New York Central Railroad Company 5% refunding and improvement mortgage series C, due 2013	6,000.00		5,742.50					5,742.50
Northern Pacific Railway Company 6% refunding and improvement mortgage series B, due 2047	10,000.00		10,962.50					10,962.50
Pennsylvania Railroad Company 30-year secured serial 4%, due 1944	6,000.00		5,337.50		$1,067.50			6,405.00
St. Louis-San Francisco Railway Company 5% prior lien mortgage series B, due 1950 (certificates of deposit)	6,000.00		5,497.50					5,497.50
Southern Pacific Oregon Lines 4½% first mortgage series A, due 1977	1,000.00				996.25			996.25
Texas and Pacific Railway Company, 4%, due 1977	5,000.00			$5,306.25				5,306.25
Western Pacific Railroad Company 5% series A, due 1946	15,000.00		7,225.00					7,225.00
Total railroad bonds—(Forward)		$ 4,010.00	$ 74,946.25	$5,306.25	$2,063.75	$4,330.00		$ 86,646.25

Exhibit A, Schedule 1 (Concluded)

Property and Restricted Funds Securities, Less Reserve for Bonds of Doubtful Value, April 30, 1937

	Face Value of Bonds or Number of Shares of Stock	Property Fund (Equipment Replacements)	Restricted Funds: Reserve Capital Fund	Restricted Funds: Life Membership Fund	Restricted Funds: International Electrical Congress of St. Louis Library Fund	Restricted Funds: Lamme Medal Fund	Restricted Funds: Mailloux Fund	Total
Total Railroad Bonds—(Forward)		$ 4,010.00	$ 74,946.25	$5,306.25	$2,063.75	$4,330.00		$ 86,646.25
Public Utility Bonds:								
American Gas & Electric Company 5% debenture, due 2028	$ 9,000.00		$ 9,596.25					$ 9,596.25
Georgia Power Company first and refunding mortgage 5%, due 1967	10,000.00		9,725.00					9,725.00
Monongahela-West Pennsylvania Public Service Company 6% debentures, due 1965	8,000.00		8,660.00					8,660.00
New York Telephone Company $4^1/_2$%, due 1939	1,000.00						$1,000.00	1,000.00
Philadelphia Company, secured 5% series A, due 1967	10,000.00		10,000.00					10,000.00
Shawinigan Water and Power Company $4^1/_2$% first mortgage and collateral trust sinking fund series A, due 1967	5,000.00		4,581.25					4,581.25
Texas Electric Service Company 5% first mortgage, due 1960	10,000.00		9,838.75					9,838.75
United Light & Power Company $5^1/_2$% first lien and consolidated mortgage, due 1959	5,000.00		4,975.00					4,975.00
Total public utility bonds			$ 57,376.25				$1,000.00	$ 58,376.25
Industrial and Miscellaneous Bonds, Etc.:								
Fidelity Union Title and Mortgage Guaranty Company first mortgage certificates (on property 75–79 Prospect Street, East Orange, N. J.), 4%, due 1944	$14,663.00	$ 977.53	$ 13,685.47					$ 13,685.47
International Match Corporation 5% convertible debenture, due 1941 (certificates of deposit)	2,550.00		2,424.15					2,424.15
International Securities Corporation of America 5% debentures, due 1947	11,000.00		11,070.00					11,070.00
New York Steam Corporation 6% first mortgage, due 1947	10,000.00		10,837.50					10,837 50
United States Rubber Company 5% first and refunding mortgage series A, due 1947	2,000.00		1,915.00					1,915.00
Total industrial and miscellaneous bonds, etc		$ 977.53	$ 39,932.12					$ 39,932.12
Municipal Bonds:								
City of Detroit public lighting $4^1/_2$% A, due 1945	$10,000.00		$ 10,262.50					$ 10,262.50
City of Union City, New Jersey, improvement bond of 1929 $4^3/_4$%, due 1945	10,000.00		10,154.50					10,154.50
New York City $4^1/_2$% corporate stock, due 1957	2,000.00				$2,204.05			2,204.05
Total municipal bonds			$ 20,417.00		$2,204.05			$ 22,621.05
Capital Stocks:								
Commonwealth Edison Company	12 shares		$ 2,892.00					$ 2,892.00
Commercial Investment Trust Corporation $4^1/_4$% preferred, series of 1935	100 shares		10,100.00					10,100.00
Consolidated Edison Company of New York, Inc., $5.00 cumulative preferred	30 shares	$ 3,060.00						
Public Service Corporation of New Jersey, $5.00 preferred	30 shares		2,958.75					2,958.75
United Gas Improvement Company, $5.00 preferred	30 shares	1,995.00	997.50					997.50
Total capital stocks		$ 5,055.00	$ 16,948.25					$ 16,948.25
Total		$10,042.53	$209,619.87	$5,306.25	$4,267.80	$4,330.00	$1,000.00	$224,523.92
Less Reserve for Bonds of Doubtful Value:								
Central of Georgia Railway Company 5% consolidated mortgage, due 1945	$ 3,000.00		$ 1,477.50					$ 1,477.50
Florida East Coast Railway Company 5% first and refunding mortgage series A, due 1974	10,000.00		9,818.75					9,818.75
International Match Corporation 5% convertible debentures, due 1941	2,550.00		2,424.15					2,424.15
St. Louis-San Francisco Railway Company 5% prior lien mortgage series B, due 1950	6,000.00		5,497.50					5,497.50
Total reserve for bonds of doubtful value			$ 19,217.90					$ 19,217.90
Total securities, less reserve		$10,042.53	$190,401.97	$5,306.25	$4,267.80	$4,330.00	$1,000.00	$205,306.02
Total Property Fund Securities		$10,042.53						
Total Restricted Fund Securities			$190,401.97	$5,306.25	$4,267.80	$4,330.00	$1,000.00	$205,306.02

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Statement of Recorded Cash Receipts and Disbursements of General Fund for the Year Ended April 30, 1937

Exhibit B

Cash on Deposit, May 1, 1936, With National City Bank of New York		$ 48,367.77
Receipts:		
Dues (including $80,634.00 allocated to ELECTRICAL ENGINEERING subscriptions)	$186,305.30	
Advertising	29,947.01	
TRANSACTIONS subscriptions	6,651.68	
ELECTRICAL ENGINEERING subscriptions	14,011.80	
Miscellaneous publications, etc	6,176.45	
Students' fees	10,413.00	
Entrance fees	7,160.63	
Membership badges	1,719.50	
Transfer fees	943.00	
Interest on investments, less purchased interest	9,057.82	
Miscellaneous	35.64	
Total receipts		272,421.83
Total		$320,789.60
Disbursements:		
Publication expense:		
ELECTRICAL ENGINEERING	$ 86,126.82	
TRANSACTIONS	3,714.89	
YEAR BOOK	3,346.15	
Miscellaneous publications, etc	4,415.05	
Administrative expenses	43,089.23	
Institute Sections	35,560.93	
Institute meetings	10,883.57	
Institute Branches	2,888.26	
American Engineering Council	13,000.00	
Traveling expenses:		
National Nominating Committee	907.38	
Geographical districts:		
Branch delegates	6,853.06	
Executive Committees	1,405.90	
Vice Presidents	281.07	
Board of Directors	6,973.49	
Institute representatives	24.00	
Forward	$219,469.80	$320,789.60
Total—(Forward)		$320,789.60
Disbursements—(Forward)	$219,469.80	
United Engineering Trustees, Inc.:		
Library assessment	8,776.30	
Building assessment	7,596.88	
Space assessment—E.C.P.D	450.00	
Engineering Societies employment service	2,257.28	
Membership Committee	7,511.80	
Standards Committee	5,513.96	
American Standards Association	1,166.67	
President's appropriation	1,791.26	
Technical Committee	190.69	
Edison Medal Committee	141.28	
Membership badges	1,765.51	
Retirement salary	2,700.00	
Finance Committee	1,600.00	
Headquarters Committee	44.85	
United States Committee of International Commission on Illumination	300.00	
Code Committee	60.00	
John Fritz Medal	50.00	
Geographical district—Paper prizes	125.50	
Transfer to reserve capital fund	7,577.50	
Total disbursements		269,089.28
Cash on Deposit, April 30, 1937, With the National City Bank of New York		$ 51,700.32

Statement of Recorded Cash Receipts and Disbursements of Property and Restricted Funds for the Year Ended April 30, 1937

Exhibit C

		Restricted Funds					
	Property Fund (Equipment Replacements)	Reserve Capital Fund	Life Membership Fund	International Electrical Congress of St. Louis Library Fund	Lamme Medal Fund	Mailloux Fund	Total Restricted Funds
Cash on Deposit, May 1, 1936, With East River Savings Bank and National City Bank of New York	$22.47		$ 4,732.99	$ 665.05	$177.63	$ 3.92	$ 5,579.59
Receipts:							
Interest on bonds			$ 297.22	$ 174.00	$240.00	$45.00	$ 756.22
Interest on bank balances			83.84				83.84
Proceeds from sale and redemption of bonds		$ 6,363.90	5,780.38	1,098.57			13,242.85
Transfer from general fund		7,577.50					7,577.50
Total receipts		$13,941.40	$ 6,161.44	$1,272.57	$240.00	$45.00	$21,660.41
Total	$22.47	$13,941.40	$10,894.43	$1,937.62	$417.63	$48.92	$27,240.00
Disbursements:							
Annual withdrawal authorized in by-laws			$ 972.32				$ 972.32
Gold and bronze replicas of Lamme Medal					$280.30		280.30
Purchase of bonds		$13,635.00	5,306.25	$ 996.25			19,937.50
All other disbursements			69.44	2.75			72.19
Total disbursements		$13,635.00	$ 6,348.01	$ 999.00	$280.30		$21,262.31
Balance on Deposit, April 30, 1937, With East River Savings Bank and National City Bank of New York	$22.47	$ 306.40	$ 4,546.42	$ 938.62	$137.33	$48.92	$ 5,977.69

A New Photoelectric Hysteresigraph

By R. F. EDGAR
ASSOCIATE AIEE

Introduction

GRAPHICAL RECORDING of hysteresis loops or magnetization curves by means of a hysteresigraph is in many instances a much more convenient way of obtaining desired magnetic data than is the usual ballistic method. Unsymmetrical hysteresis loops, for example, may require considerable laborious procedure if obtained in the usual manner, but are easily recorded by some types of hysteresigraphs. The photoelectric hysteresigraph described herein is an instrument which readily records initial magnetization curves or any desired symmetrical or unsymmetrical hysteresis loops.

Several different forms of hysteresigraphs have been described. They are of 2 general types, depending upon whether the test specimen is magnetized by alternating current or by direct current. An a-c hysteresigraph may employ a cathode-ray oscillograph arranged in such a manner that the horizontal deflection of the electron beam is made proportional to magnetizing force while the vertical deflection is made proportional to induction.[1] Other types of a-c hysteresigraphs also have been described.[2,3] Eddy currents within the specimen tend to distort the shape of the recorded hysteresis loop, making laminated specimens necessary. A–c hysteresigraphs record only cyclic loops. Usually symmetrical loops are recorded, but minor or unsymmetrical loops may be obtained if the power supply furnishing the magnetizing current can be arranged to introduce current of suitable harmonic frequency superimposed upon the fundamental component of the magnetizing current. A-c hysteresigraphs appear to have been applied principally to testing sheet materials of low loss and high permeability.

An early form of cathode-ray tube hysteresigraph,[4] and a magnetic curve tracer described by Ewing,[5] may be used to obtain either cyclic a-c loops or d-c loops formed by slowly varying the magnetizing current through the desired cycles. In these devices part of the magnetic circuit is through air, and the strength of the magnetic field in the air path is measured as an indication of the induction in the specimen while the magnetizing current is taken as a measure of magnetizing force. Introduction of an air gap in the magnetic circuit, however, tends to prevent uniform magnetization of the specimen with resulting errors in the measurement of both induction and magnetizing force. A recent magnetic curve tracer[6] obtains d-c loops and is applicable to the testing of specimens in a closed magnetic circuit. It employs a search coil interlinking the specimen and a fluxmeter having its restoring torque automatically counterbalanced throughout its range of deflection so that it is accurately responsive to slow flux changes.

D-c hysteresigraphs do not require laminated specimens because the desired cycle of magnetization may be carried out so slowly that eddy currents do not become large enough to affect the results even if solid specimens are used. Initial magnetization curves and unsymmetrical hysteresis loops, as well as symmetrical hysteresis loops may be obtained. Besides being applicable to the testing

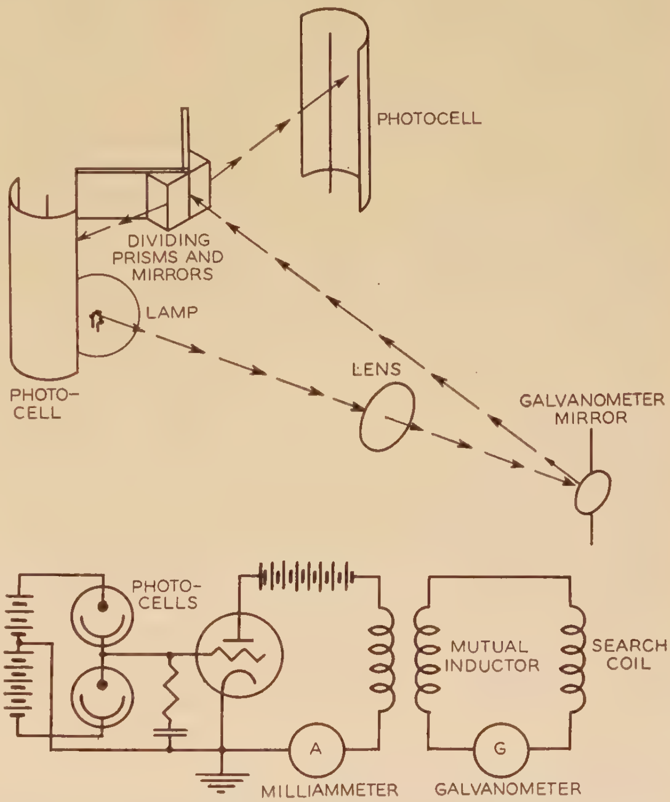

Figure 1. Optical system and electrical circuit for photoelectric fluxmeter

of electrical sheet steels the d-c hysteresigraph may also be used in testing magnet materials, specimens of which are commonly solid rather than laminated.

Description

The hysteresigraph described herein is a d-c instrument which may be used to test either laminated or solid specimens in ring or bar form. For bar specimens it is connected to a permeameter in the same manner as the common ballistic galvanometer equipment. When used with the saturation permeameter[7] measurements may be made to a mag-

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R. F. Edgar is employed in the general engineering laboratory of the General Electric Company, Schenectady, N. Y.

1. For all numbered references, see list at end of paper.

netizing force of 3,000 oersteds or higher. The equipment is sturdy and does not employ any delicate instruments which require careful handling, fine adjustment, or special mounting.

The Photoelectric Fluxmeter

The heart of the instrument is a photoelectric fluxmeter[8] which is responsive to slow changes in flux linking a search coil, and provides an indication which remains constant without drift as long as the flux linking the search coil remains constant. Elementary diagrams of the fluxmeter are shown in figure 1. A galvanometer and search coil are used, and in series with them is connected the secondary coil of a mutual inductor. By means of an optical system and 2 photoelectric cells connected in a vacuum-tube circuit the galvanometer deflection is maintained at zero, the current in the primary coil of the mutual inductor being automatically varied so as to induce a voltage in the secondary coil equal and opposite to any voltage which may be induced in the search coil by a change of flux interlinking it. The change of interlinkage in the secondary coil caused by the change in primary current is then equal and opposite to the change of interlinkage in the search coil. The variation in primary current is, therefore, a measure of the flux variation in the search coil. Since the galvanometer remains at the zero position its suspension torque does not act to cause drift, and the primary current varies only when the flux linkage in the search coil varies.

The optical system and electrical circuit is adapted from the photoelectric recorder.[9] The beam from the galvanometer mirror is focused upon a set of mirrors and prisms which divides it into 2 parts and reflects each part into a photocell. Deflection of the galvanometer causes the light in one cell to increase and that in the other to diminish. The 2 photocells are connected in series with a voltage source, and to the grid of a vacuum tube in such a way that any unbalance of the divided light beam between the 2 cells causes a change in the grid voltage with a resultant change in plate current. The plate current, supplied by a second voltage source, flows in the primary coil of the above-mentioned mutual inductor. The direction of current flow is such that any change caused by a deflection of the galvanometer light beam causes a change of flux linking the secondary coil of the mutual inductor, tending to correct the galvanometer deflection and restore the orginal light balance.

A slight deflection of the galvanometer is evidently necessary to initiate the corrective change of plate current. This, however, is very small, and the final position when a new balance is restored is almost exactly the same as the original position. The photocells are of the vacuum type and are operated at a high voltage so that the current through them depends upon the light falling upon them and is nearly independent of voltage variation. The current for any constant value of grid voltage must be the same in both photocells, since they are in series, and any difference in current would necessarily alter the charge on the grid capacitor and change the grid voltage. The light division between the 2 cells must, therefore, be the same also, which means that the final position of the galvanometer beam must be the same for all steady values of flux linking the search coil. This was demonstrated in the development of the apparatus by setting up in place of the galvanometer a pivoted rod carrying a galvanometer mirror and having an arm 50 centimeters long projecting at right angles. The outer end of the arm was held lightly against the screw of a rigidly mounted micrometer. Turning the micrometer screw caused the end of the arm to move, rotating the mirror as it would rotate if mounted in the usual manner in a galvanometer. It was found that a motion at the outer end of the arm of 0.001 centimeter was sufficient to change the plate current of the tube from one extreme to the other. This corresponds to a light beam deflection of 0.0008 centimeter at the dividing prisms, and would be equivalent to a deflection of 0.004 centimeter on a scale set up at the customary meter distance.

Angular movement of the galvanometer coil equivalent to 0.001 centimeter deflection at the end of a 50 centimeter arm causes an interlinkage change in the galvanometer coil of about 30 maxwell-turns with the coil and field strength employed. In practice the galvanometer is used without any external shunt or series resistance, but is connected directly to the search coil and mutual inductor secondary winding. Since the total number of interlinkages in a circuit tends to remain constant, the difference between the change of flux linkages in the secondary coil of the mutual inductor and that in the search coil is about equal to that in the galvanometer coil. This difference is, therefore, about 30 maxwell-turns for a full-range change in the search coil. With the tube used in this test, the full-range change of plate current was

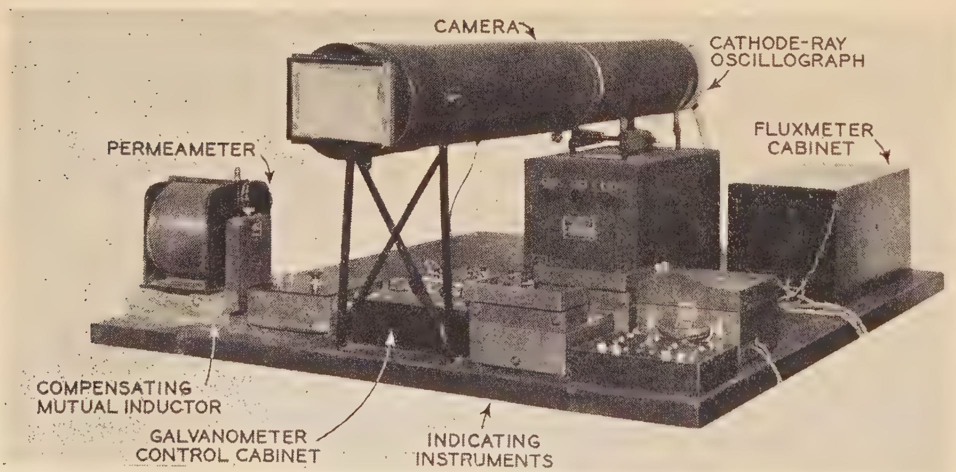

Figure 2. Photoelectric hysteresigraph

about 27 milliamperes. A mutual inductor of 10^7 secondary maxwell-turns per primary ampere is used, so that full-range change of flux linkages was about 270,000 maxwell-turns. The difference between the actual change of interlinkage in the search coil and that indicated by the change in plate current through the primary winding of the mutual inductor is then about 0.0011 per cent. The tube has since been changed to a type which permits a larger change of plate current and has a higher mutual conductance so that the present figure is somewhat less.

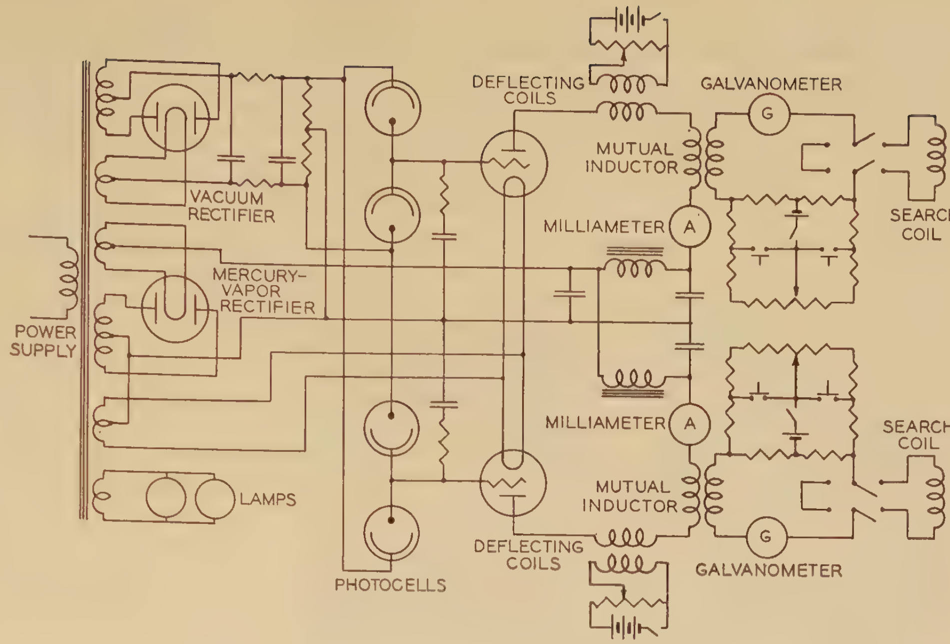

Figure 3. Photoelectric hysteresigraph circuit diagram

The amount of deflection during the flux change depends upon the rapidity of the flux change, the constants of the grid and plate circuits, and the characteristics of the galvanometer and its circuit. When the apparatus is used merely as an indicating fluxmeter this deflection is not important, since it returns to the small equilibrium value when the instrument indication becomes steady and can be read. It is necessary only that the deflection be small enough so that there is not sufficient suspension restoring torque to cause measurable drift during the flux change.

For use in automatic curve tracing, however, it is necessary that the current in the primary coil of the mutual inductor shall change accurately in agreement with the changing of interlinkages in the search coil. There must be no measurable lag between them. The galvanometer coil must have sufficiently low inertia to quickly begin to deflect and initiate a corrective change in the plate current when there is a change in interlinkages in the search coil. The capacitance in the grid circuit must be low enough so that the grid voltage quickly changes when there is an unbalance in the photocell circuit. The inductance in the plate circuit must be low enough to permit quick changes of plate current. It has been found that a portable reflecting galvanometer is entirely satisfactory, and no difficulty is experienced in making the constants of the circuits correct for accurate response to slow changes of interlinkage.

The accuracy of the measurement is not affected by small changes in supply voltage, vacuum-tube characteristics, photocell sensitivity, or light intensity. The optical system and photoelectric circuit are similar to those of the photoelectric recorder in being self-compensating for all normal changes in these variables.

The photoelectric fluxmeter is equivalent to a galvanometer of infinitely long period, in that it responds accurately to slow flux changes and its indication remains constant at any part of the range without drift. Moreover, the output of the instrument, instead of being merely deflection of a light beam on a scale, is in the form of electric current of sufficient power to operate sturdy and relatively insensitive indicating instruments or recording devices.

The Hysteresigraph

The photoelectric hysteresigraph as illustrated in figure 2 consists of 2 such fluxmeters combined with a cathode-ray oscillograph. Magnetic deflection coils fitted to the oscillograph tube are connected in the plate circuits of the fluxmeters so that one fluxmeter causes vertical deflection of the electron beam and the other causes horizontal deflection. The search coil of the first fluxmeter is linked by the specimen under test and that of the second lies adjacent to the specimen but is not linked by it,[7] so that one fluxmeter measures induction changes and the other magnetizing force changes. Bar or strip specimens may be tested at high magnetizing force in the saturation permeameter. The hysteresigraph is adaptable to any type of permeameter in which the magnetizing force can be measured by means of a search coil as described, but which requires no varying compensating adjustment over the range of test. Ring specimens may be tested by using only one fluxmeter, a portion of the magnetizing current being passed directly through the horizontal deflection coils.

The circuit diagram for the hysteresigraph is shown in figure 3. It is similar to that of figure 1, the batteries being replaced by rectified a-c power sources, and 2 complete fluxmeters being provided. A small dry cell with fixed and variable resistors in each galvanometer circuit provide a means of balancing out any small thermoelectric or other voltage which may be present. Push buttons in this circuit facilitate shifting the plate current at will so

that it can be set at any desired value for the beginning of a test, and switches enable the search coils to be inserted in or removed from the circuit.

Figure 4 shows the arrangement of galvanometers, photocells, optical system, and vacuum tubes for both fluxmeters in one cabinet. Transformers, capacitors, and wiring are mounted on the under side of the subbase. The galvanometers are of the portable type[10] having sturdy suspensions and require no careful leveling or delicate adjustment. Moving systems of relatively low resistance are used. Stops are provided limiting the deflection to a small angle and preventing the beam from being thrown entirely off the dividing mirrors at any time. The light beams are supplied by 32-candlepower 6-volt automobile headlight bulbs in ventilated housings, and convex lenses in adjustable tubes. The photocells and prisms are enclosed in housings which prevent entrance of stray light. Voltage is supplied to the photocells by a vacuum rectifier tube through a resistance-capacitance filter circuit. Power is supplied to the plate circuits by a mercury-vapor rectifier tube having a low voltage drop, and a filter circuit of inductance and capacitance.

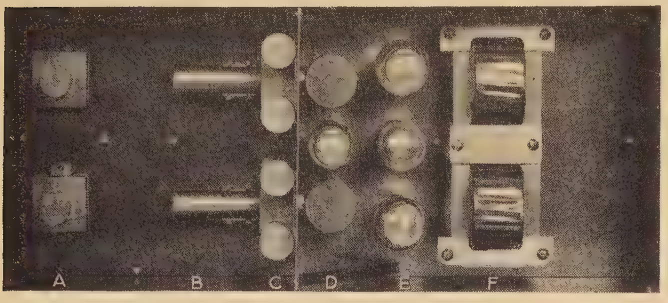

Figure 4. Interior view of fluxmeter cabinet

A—Galvanometers
B—Lens mountings
C—Photocell housings
D—Lamp housings and rectifier tube
E—Vacuum tubes and mercury-vapor rectifier
F—Filter reactors

Figure 5 shows the cabinet containing the 2 mutual inductors and the galvanometer control circuits. The 2 mutual inductors are each in 2 sections, astatic to uniform external fields, and are so mounted as to have no inductive coupling between them.

The cathode-ray oscillograph has a tube with a screen 7 inches in diameter, and is equipped with its own power supply. The magnetic deflection coils are located on 2 yokes of nickel-iron alloy having high permeability and low hysteresis, placed so as to produce magnetic fields at right angles to each other and to the electron beam. Two sets of coils are placed on each yoke, one being connected in the fluxmeter circuit and the other being connected to a battery and adjustable resistance. The second set is used to provide adjustment of the zero position of the electron beam.

A photographic record of the pattern traced on the fluorescent screen is made by means of the camera attached to the oscillograph. A piece of fiber tubing is fitted to the shield around the oscillograph tube. In the center is a lens equipped with a shutter and cable release, and at the end provision is made for exposing film or sensitized paper in 5-inch by 7-inch film holders. The shutter is normally used in the "bulb" position, and held open by means of the cable release while the record is being obtained.

A motor generator set has been provided to supply the magnetizing current for the specimen. Field control of the separately excited generator is used to obtain the desired maximum current. Reversing contactors included in the armature circuit of the generator permit a cyclic state of the sample to be obtained quickly, if desired, before tracing the loop. The magnetizing current is varied through the desired cycle by means of 2 rheostats having the resistance elements connected in parallel across the power supply line from the generator and the sliders connected to the magnetizing coil. The sliders are mechanically coupled together in such a way that moving them from one extreme to the other causes the magnetizing current to vary from a maximum value through zero to an equal and opposite maximum value. Not only symmetrical cycles, but any desired unsymmetrical and complicated cycle can be easily obtained.

When specimens are tested in the saturation permeameter a compensating variable mutual inductor may be used to compensate for any desired portion of the area of the potential coil measuring induction. By properly adjusting this inductor the space inside the coil but outside the specimen may be compensated for so that total induction in the sample is recorded. If desired, the entire area of the potential coil may be compensated for, so that intrinsic induction in the specimen is recorded. The primary coil is connected in series with the magnetizing coil of the permeameter, and the secondary coil is connected in series with the search coil measuring induction. The magnetizing force in the saturation permeameter is very

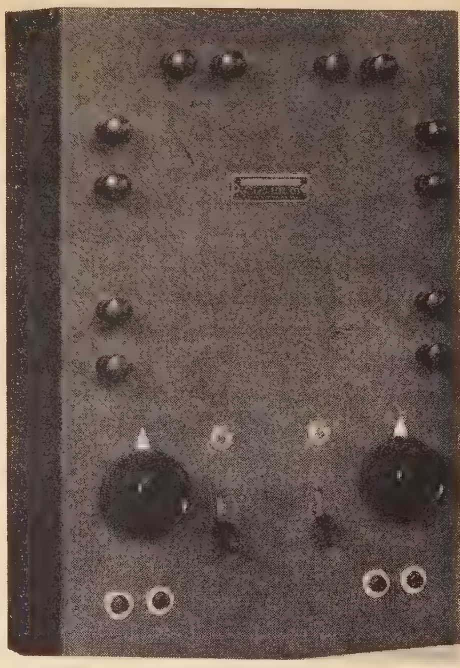

Figure 5. Galvanometer control cabinet

nearly proportional to the magnetizing current, so that by means of the compensating inductor a component of flux linkages proportional to the magnetizing force is introduced into the circuit containing the induction search coil. Since the flux linkages in this search coil due to space outside the specimen, or that due to the difference between total and intrinsic induction in the specimen, is proportional to magnetizing force, these flux linkages can be compensated by means of the compensating inductor.

Records

Samples of records obtained with this equipment are shown in figures 6 and 7. Figure 6 shows portions of symmetrical hysteresis loops for 3 magnet materials. Figure 7 shows the upper portion of a loop having several minor loops traced in the second quadrant.

The co-ordinate lines are put in after the loop has been traced by switching the search coils out of the circuit, setting the plate current for one fluxmeter successively at values representing desired values of induction and varying the other through its entire range, then setting the plate current for the other fluxmeter successively at values representing desired values of magnetizing force and varying the former through its entire range. Values of plate current representing these quantities are calculated from a knowledge of the cross-sectional area of the sample, the number of turns and the areas of the search coils, and the mutual inductance of the inductors.

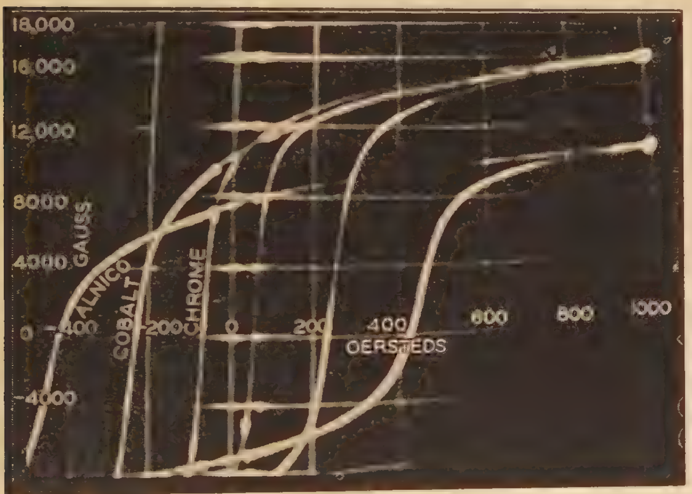

Figure 6. Hysteresis loops for magnet materials

Application

The hysteresigraph has been found particularly useful in the study of magnet materials, and in obtaining data for magnet design. Recent development of improved materials has brought about the use of permanent magnets in applications not previously considered practical, particularly in applications where the magnet may be subjected to varying external reluctance or strong demagnetizing magnetomotive force. For these applications the second quadrant of the symmetrical hysteresis loop alone is not sufficient for design calculations, but minor loops in this quadrant are also necessary. Figure 7 illustrates the type of data required.

Occasions frequently arise in which magnetic characteristics of a piece of equipment are desired for a particular type of unsymmetrical cycle. The hysteresigraph has been found to be a convenient instrument for obtaining such data.

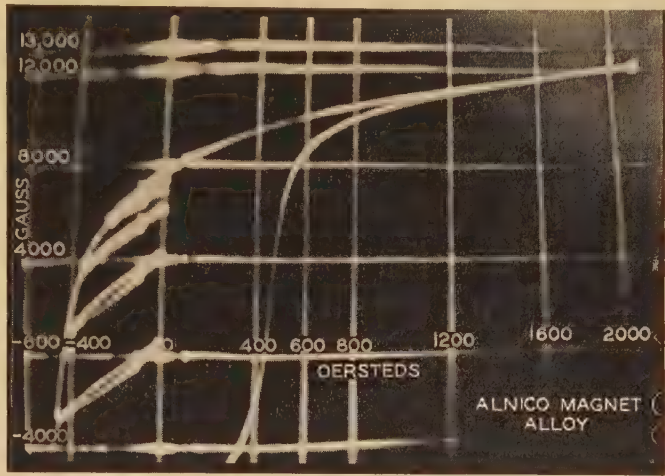

Figure 7. Hysteresis loop for magnet material showing minor loops in the second quadrant

Conclusions

Development of the photoelectric fluxmeter and hysteresigraph was accomplished by combining only apparatus of known and tried characteristics to form a sturdy and accurate instrument simple to adjust and to operate. Testing of magnetic materials and of electrical equipment is facilitated, and magnet design data, not readily obtainable with other forms of testing equipment, are made available.

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Low-Current Ignitors

By A. H. TOEPFER
ASSOCIATE AIEE

SLEPIAN AND LUDWIG'S discovery of the ignitron[1] principle of initiating the cathode spot of an arc has been followed by intensive investigation of the factors affecting the design and operation of the ignitron. Many of the design features of the ignitron follow conventional mercury-arc-rectifier practice. The distinguishing feature of the ignitron is the ignitor. An ignitor is an electrode of high resistivity material which is partially immersed in the cathode mercury. On sending a sufficiently large current through the ignitor into the mercury, a cathode spot forms upon the mercury at the ignitor mercury junction. The current to accomplish this varies in an inverse manner with the resistivity of the ignitor so that it is necessary to use relatively high resistivity material for practical ignitors. In practice the ignitor is connected to a suitable source of power with some means of switching so that the arc may be started at the proper time during the interval when the ignitron anode voltage is positive.

The most generally used circuit uses a thyratron for controlling the ignitor current as shown in figure 1.

When the grid control voltage of the thyratron and the anode voltage first become positive, the ignitor current flows and increases at a rate determined by the circuit until an arc starts in the ignitron. The current taken by the thyratron then drops to a low value depending on the relative arc drops of the thyratron and the ignitron and the resistance of the ignitor circuit. Generally this value is close to zero. The voltage across the ignitor at the same time drops to a few volts. Figure 2 shows approximately how the starting volts and amperes vary during operation.

The maximum instantaneous value of the current taken by the thyratron is many times larger than the average. It is necessary to use thyratrons with current ratings at least as large as the maximum current peaks required by the ignitors because their cathodes cannot repeatedly stand even momentary overloading without damage.

It is desirable to develop an ignitor requiring as little current as possible for several reasons. The smaller size thyratrons are cheaper than the larger, and usually the heating time of the smaller thermionic cathodes is shorter. If the starting current is reduced without changing the voltage, the load current is shifted from the ignitor circuit to the ignitron more readily at light loads. It is, therefore, more desirable to effect a reduction in starting current than to produce a cheaper thyratron to handle the ignitor load.

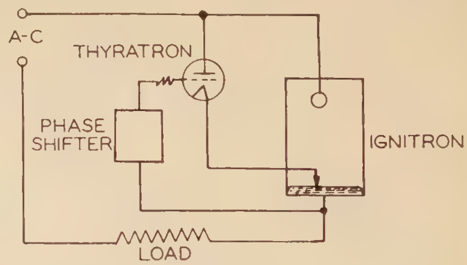
The theory advanced by Slepian and Ludwig[1] for the formation of the cathode spot at the ignitor mercury junction directs attention to the high current density and corresponding voltage gradient developed there, and points out the similarity between these conditions and the conditions existing at the last points of contact of separating electrodes. Other workers have used essentially the same picture.[2,3] Experience indicates that a material must satisfy the following conditions to be practically suitable for ignitors.

1. It must not be wet by mercury.
2. It must be workable.
3. It must not deteriorate in the arc.
4. It must have the proper electrical resistance.

The theory of Slepian and Ludwig suggests that the nature of the contact between the mercury and ignitor at the ignitor mercury junction is important. Hence, it is not surprising that if a material is wetted by the mercury during operation as an ignitor the starting current usually jumps to high values which may damage the thyratron. A convex meniscus seems to be necessary for low starting currents. If the material is wetted by the mercury a concave meniscus is obtained usually with large starting current. Also under these conditions the cathode spot tends to anchor at the ignitor instead of moving away from it in the usual way, and may damage it. This requirement eliminates many materials.

The substances which have been found to be useful ignitor materials are generally very hard in their crystalline form. Some of these materials are silicon carbide, boron carbide, and materials known under the trade names of Carborundum, Globar, and Silit. Shaping, mounting, and making electrical connection to these materials offers difficulties. Globar is easy to work when made up in high resistivity rods, but if processed to reduce the resistivity they become difficult to work because of increased hardness.

Figure 1



The need for working arises because it had been found desirable to shape ignitors to a point because this decreased the starting current. For example, comparing an ignitor made of quarter-inch rod and one made of the same material ground to a point, the latter required about one

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1. For all numbered references, see list at end of paper.

third of the current required by the rod at an increase in voltage of 20–25 per cent. The increase in voltage is due to the increase in the resistance of the ignitor due to reducing the section.

The cathode spot starts at the ignitor afresh each cycle and then does not have time to get very far away from it in the conducting period. Ignitrons also are usually built with the anode close to the cathode and often operate red hot. Hence, the ignitor frequently is required to run hot because it has little chance to dissipate heat through the ignitor lead or the mercury. Under these conditions the material must be stable. Materials have been found and are used that show no sign of deterioration, wear, or erosion after thousands of hours operation as ignitors. Some appear to have unlimited life.

The electrical characteristics depend on the resistivity and the geometric form of the ignitor. The geometric form and dimensions need to be a compromise between several conflicting conditions.

It is desirable to have the area of the ignitor actually under the mercury as small as possible, as this makes the ratio of the useful current which flows in the close vicinity of the junction, to the total current large. Also, it is desirable to make the length of the ignitor above the mercury as short as possible to reduce the voltage drop required to send the starting current through the length of the ignitor. The splashing of the mercury sets limits to what may be done in both of these directions. To avoid missing due to the ignitor losing contact with the mercury, it has been found necessary to use immersion depths of the order of a quarter of an inch. The distance from mercury to the conducting head, holder, or ignitor lead must be of the order of one half of an inch to prevent short circuiting of the ignitor by the splashing of the cathode mercury. Such short circuits may damage the cathode of the control tube if too much current passes through the circuit. Hence, we have the length fixed at $^3/_4$ of an inch plus the length of a head, or additional length to provide for some sort of mounting to make connection to the ignitor lead.

The thickness and shape are also reached by compromise between mechanical and electrical characteristics. The ignitor materials are brittle, therefore, they must be made in such diameters and shapes which will be strong enough to stand handling in assembly and the forces due to mercury when moving the ignitrons or during operation when some force is exerted by the mercury vapor and the motion of the mercury under the influence of the cathode spots. The shape generally used is approximately that of a cantilever beam of uniform strength. A typical ignitor is shown in figure 3. The tip diameter is of the order of 0.080 to 0.090 inch.

Figure 4

W—Width of slot

D—Depth of tip immersion

S—Surface tension of mercury = 0.0475 grams per millimeter

Pressure of immersed mercury = 0.0136 grams per square millimeter

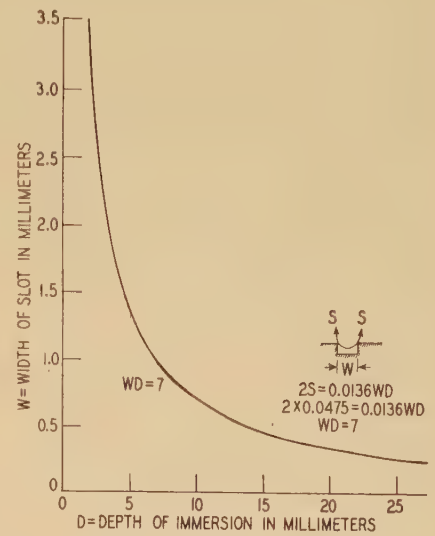

Table I

Ignitor	Starting Amperes Before Slotting	Starting Amperes After Slotting	Starting Volts Before Slotting	Starting Volts After Slotting	Current Ratio After Slotting Before Slotting
PAN 9	24	11	40	42	0.46
PAN 14	20	7	50	50	0.35
PAL 15	21	12	43	45	0.57
PAH 20	18	9	38	40	0.50
PAH 8	24	11	50	50	0.46
PAN 19	14	7	75	80	0.50

The use of such a shape has a definite effect on the starting volts and amperes as mentioned before. For a definite size and shape of ignitor the starting voltage is directly and the starting current inversely proportional approximately to the resistivity of the material used. Thus increased resistivity generally means increased voltage and decreased current. The law has not been definitely established but examination of the characteristics of a large number of ignitors shows the trend toward such a law. The most desirable resistance to use is governed by the voltage and current limits that can be tolerated. The upper voltage limit is generally set at 100 volts for the present though it is desirable to have it as low as can be obtained. Many ignitors require less than this maximum limit. The current for an ignitor of a resistance that will give starting voltage of 100 volts would be more or less constant in value from one igniter to another if uniformly shaped ignitors were made of a material of a certain resistivity, but it happens that the problem of manufacturing ignitors is far from being as simple as that. The problem of wetting has driven the ignitor maker to treat ignitors, or make them of certain materials by processes that are

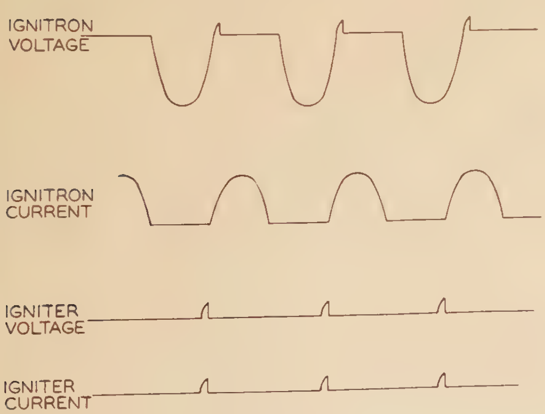

Figure 2

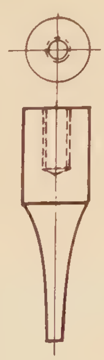

Figure 3

difficult to control and repeat exactly. Hence, the product varies in starting characteristics so an upper limit to the current required is set and the ignitors accepted if the current is less than 15 amperes and the voltage less than 100 volts.

The current is influenced a great deal by the surface of the part of the ignitor immersed in the cathode mercury. An ignitor with a smooth polished surface requires more current than one with a rough surface though the resistivities are the same. One may easily reduce the starting current, without affecting the voltage, by covering part of the immersed surface with insulation. However, fastening a suitable insulator on an ignitor is difficult and has been applied only in laboratory experiments.

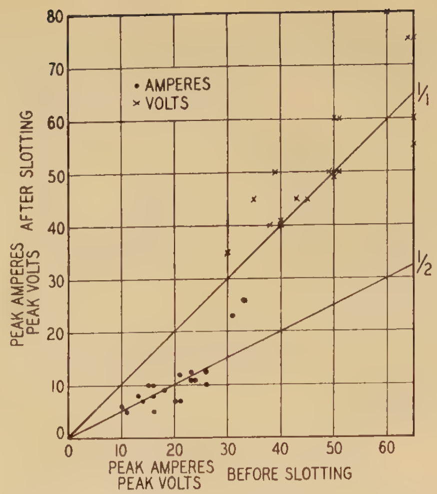

Figure 5. Effects of slotting on starting volts and amperes

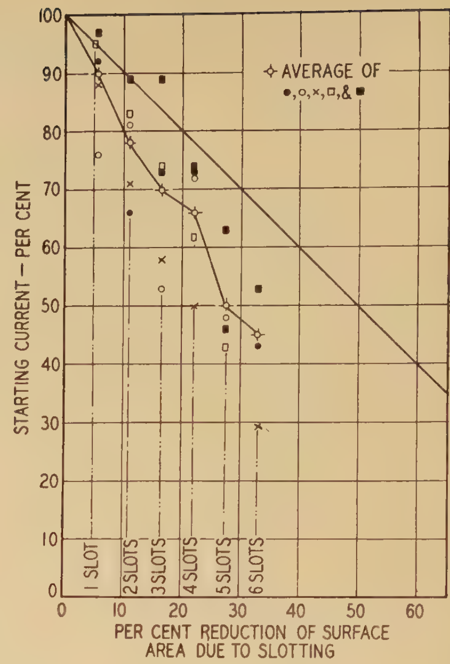

Figure 6

Slepian suggested a very effective method of reducing the surface area of the ignitor which could come in contact with the mercury and at the same time not appreciably increasing the resistance through the ignitor to the mercury junction. He estimated that the mercury would not enter slots of the order of one millimeter wide at ordinary ignitor immersion depths due to the high surface tension of the mercury. A simple experiment with 2 glass plates immersed in mercury proved the theory and calculations were made to show the relationship between the width of slot and depth of immersion when the surface tension forces just balance the static pressure. The results of these calculations are plotted in a curve, figure 4.

If the mercury level stayed always constant, the ideal slot would vary in width from tip to mercury surface. An ignitor with such slots has not been produced. It was convenient to take some of the present design of boron carbide ignitors which have a tip diameter of 0.080 or 0.090 inch and cut slots which were approximately 0.020 inch wide. Six slots were cut in each ignitor.

A few of the results are tabulated in table I.

A large number of ignitors were tested and the results spotted on figure 5. This shows the effect of slotting quite clearly. The slight increase in voltage may be due to the increase in resistance due to the cutting away of material. The current was reduced to nearly one half of the original. The picture figure 7 shows several slotted ignitors and an unslotted one for comparison.

It was observed that the current reduction was greater than the reduction in area. This was investigated by cutting one slot at a time and measuring the current after each slot was cut. The results are shown in figure 6, which shows starting current in per cent plotted against reduction of surface area in per cent.

An examination of the surface of the mercury at the slots and between slots showed that the line of contact of the mercury with the ignitor between slots was not a plane curve but was lower at the slots than between the slots. This fact coupled with a change in current distribution in the ignitor and mercury may account for the additional reduction in current.

The minimum current and voltage at which an ignitor will initiate an arc has not been determined. If the currents can be reduced sufficiently it becomes possible to use smaller and cheaper thyratrons and other means of supplying the ignitor current. Some ignitors do not suffer when back current passes through them so if the current requirement is reduced other methods of control become possible which, at present, are too costly or unwieldy to be useful.

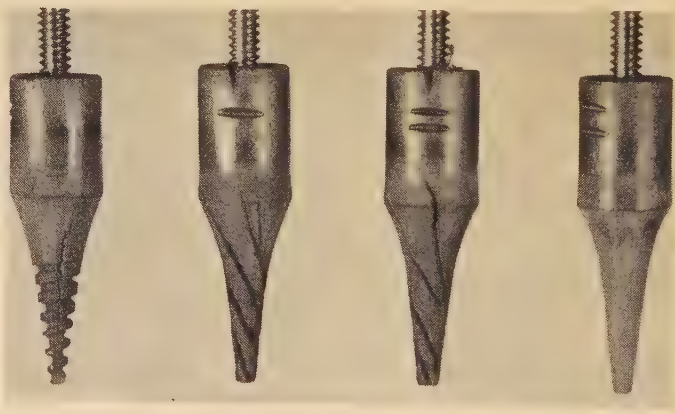

Figure 7

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Approximating Potier Reactance

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POTIER REACTANCE is a somewhat fictitious reactance, because it is a combination of reactance, change of saturation, and change of flux form. Nevertheless, it is sometimes a rather useful fiction because it can be easily tested, and because it can be used to obtain full load field currents of synchronous machines when only the no-load saturation curve is available. It is also useful for determining effects of saturation on stability.

The following discussion attempts only to give 3 approximate empirical methods of calculating X_p and to show the probable accuracy of the methods for typical machines. The value of the methods can best be judged by a comparison of calculated values with test values, as is done in table I and in figures 6 to 9. This is because the equations used involve certain approximations and in addition are made up of 3 terms, all of which must be calculated by approximate or by semiempirical formulas. A discussion of some of the difficulties involved in the accurate predetermination of X_p is also included, but formulas for accurate calculation are not developed.

Potier reactance is tested as the difference between 2 saturation curves, one taken at no load, and the other taken at full current, zero power factor. These curves for a typical machine are shown in figure 1, and the geometrical construction usually employed in obtaining the reactance from these 2 curves is shown by the triangle *ABC*. (The altitude of the triangle is the Potier reactance drop in volts so that per cent X_p equals $(CD/VB') \times 100$.) Expressed in words, the process is to find the triangle which will fit between the 2 curves at both the location *ABC* and the location *A'B'C'*, where the point *A* is at the voltage at which the reactance is desired.

The process of finding a triangle that will fit at 2 places is simple, but, as might be supposed, the actual value of reactance obtained will depend on the voltage at which the upper triangle is constructed. To illustrate this, figure 2 has been drawn showing Potier reactance of the machine of figure 1 plotted against terminal voltage, and reference can be made to several similar curves in the first article of the bibliography. Another difficulty associated with the process of fitting 2 triangles is that of determining when they fit, and to illustrate this point, the curve of figure 3 has been drawn. This curve is identical with figure 2 except that the field currents at any point on the given test saturation curves of figure 1 have been assumed to be accurate only within ±1 per cent, and the resulting effect on Potier reactance has been shown as a crosshatched band. Stated in words, this question of fit resolves itself into the fact that since Potier reactance is measured geometrically as a voltage drop parallel to the air-gap line, it can be measured accurately only when the slope of the no-load saturation curve differs appreciably from that of the air-gap line. In the following discussion, therefore, the value of X_p will not be discussed below the point where the slope of the no-load saturation curve at the peak of the Potier triangle equals twice the slope of the air-gap line.

Analysis of Machine Internal Conditions Affecting X_p

To get a better physical picture of what constitutes Potier reactance, let us first consider in detail the fluxes existing when a machine is operating as a synchronous condenser, that is, at the point *A* in figure 1. Under these conditions, the internal or air-gap voltage is ordinarily considered to be greater than the terminal voltage, because of reactance drops. The end winding reactance, for example, can be considered merely as external reactance so that all machine fluxes are raised by the drop across the end winding reactance. The slot reactance causes the

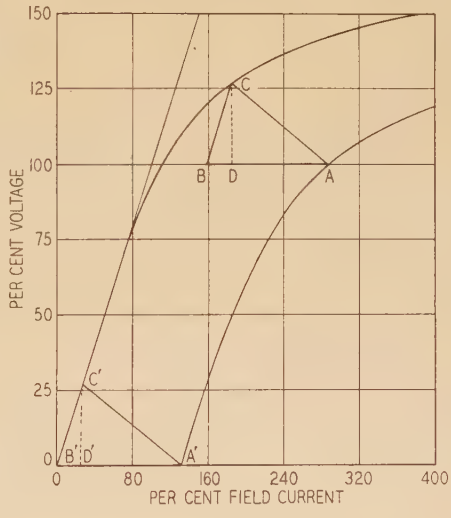

Figure 1. Typical synchronous-machine saturation curves showing construction for obtaining X_p. (These are actual test curves)

flux in the air gap to be greater than that in the core, since part of the flux crossing the gap is shunted across the slots (because of the armature current) and does not reach the core, but only cuts the conductors near the top of the slot. Similarly, part of the flux through the poles does not even cross the gap, but crosses directly from the side of one pole to the side of the next, and may be said to produce a field reactance drop quite similar to the slot winding or end winding reactance drop.

In figure 4, the no-load saturation curve has been broken up into its component parts, representing pole, air-gap,

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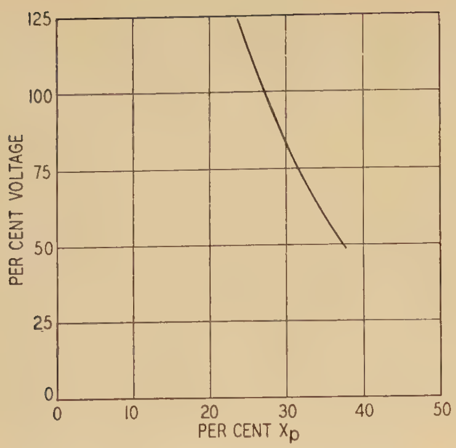
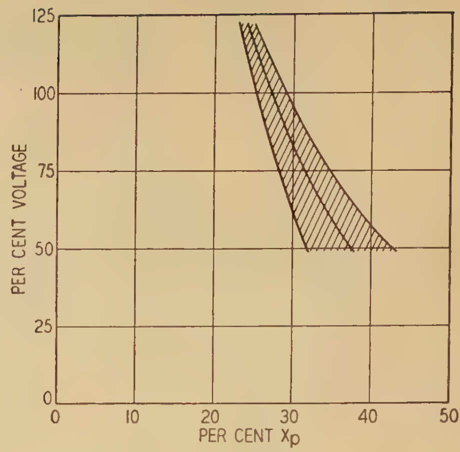


Figure 2. X_p as obtained from the test curves of figure 1

Figure 3. Inherent chance of error in testing X_p



This curve is the same as that of figure 2, except that the field currents at any point on the given test saturation curves of figure 1 have been assumed to be accurate only within ±1 per cent, and the resulting effect on X_p has been shown as a crosshatched band

tooth, and core saturation. To be exact, each of these components should be broken down into still smaller parts, and should vary with load conditions on the machine, but the additional complications would only confuse the relations to be brought out now. The reactance drops mentioned above have been shown in figure 4, so that the points *P*, *G*, *T*, and *C* represent the internal voltages in the pole, air gap, teeth, and core, respectively. Figure 4 can be simplified by making the following assumptions: (1) the core saturation is negligible; (2) the saturation in the teeth is largely at the tips of the teeth (see appendix), so that the flux determining saturation in the teeth can be assumed to be the same as the flux in the air gap; and (3) the effective flux in the pole can be considered to be increased above no-load conditions by the amount of transient reactance drop, since transient reactance represents leakage reactance plus flux which crosses between poles and does not link the field winding. Transient reactance flux is not identical with leakage flux because of harmonics, change of wave form, saturation and other factors, but in developing the following approximate formula, it will be considered identical.

Table I. Comparison of Test and Calculations

Machine No.	Machine Kva	Machine Poles	Per Cent Reactances X_d	X_l	X_d'	Test	Per Cent Potier Reactance: Calculated by Eq 1	Difference	Average Difference	Calculated by Eq 2	Difference	Calculated by Eq 3	Difference	Saturation Data: Pole AT / Tooth + Pole AT	K_{nl}	K_q
1	200	6	108	6.3	19.9	19.8	18.0	+1.8		14.8	+5.0	15.9	+4.0	0.88	1.19	1.37
2	5,000	8	142	13.7	35.3	26.0	26.4	−0.4		27.3	−1.3	28.3	−2.3	0.59	1.12	1.43
3	10,000	8	170	13.5	41.1	31.1	29.7	+1.4	+3.4	30.8	+0.3	33.0	−2.0	0.59	1.09	1.49
4							25.9	+5.2						0.45		
5	100	10	160	12.7	33.7	31.6	27.1	+4.5		25.9	+5.7	27.0	+4.6	0.68	1.24	1.94
6	500	10	129	9.4	28.5	22.9	20.7	+2.2		21.4	+1.5	22.8	+0.1	0.59	1.17	1.49
7	800	14	71	8.6	21.7	15.9	18.3	−2.4		16.8	−0.9	17.4	−1.5	0.74	1.3	1.7
8	200	18	124	17.0	33.0	26.6	28.9	−2.3		27.0	−0.4	26.4	+0.2	0.75	1.21	1.82
9	220	18	125	16.0	32.3	25.3	28.2	−2.9		26.2	−0.9	25.9	−0.6	0.75	1.18	1.43
10	250	18	149	9.3	17.6	16.5	15.3	+1.2	+2.1	14.5	+2.0	14.1	+2.4	0.73	1.15	1.42
11				8.3	16.7		13.6	+2.9						0.63		
12	450	18	132	14.7	33.8	25.2	28.2	−3.0		26.7	−1.5	27.1	−1.9	0.71	1.12	1.28
13	850	18	153	16.2	36.6	28.6	26.2	+2.4		29.0	−0.4	29.2	−0.7	0.49	1.09	1.42
14	625	22	118	14.8	32.8	33.3	30.5	+2.8		26.1	+7.2	26.3	+7.0	0.87	1.24	2.06
15	875	24		19.1	44.0	38.2	34.6	+3.6		34.7	+3.5	35.2	+3.0	0.62	1.16	2.46
16	300	26		22.4	39.7	32.5	29.7	+2.8	+0.9	33.2	−0.7	31.8	+0.8	0.42		2.20
17							33.5	−1.0						0.52		
18	750	26	80	10.8	23.4	15.3	18.7	−3.4	−4.2	18.7	−3.4	18.7	−3.4	0.63	1.44	2.10
19							20.3	−5.0						0.75		
20	1,100	28	127	15.6	36.8	31.0	28.1	+2.9		28.9	+2.1	29.3	+1.7	0.59	1.09	1.73
21	2,200	30	102	15.0	32.5	27.4	28.3	−0.9		26.0	+1.4	26.0	+1.4	0.75	1.23	1.93
22	375	32	116	19.3	38.4	35.6	35.6	0	0	31.3	+4.3	30.9	+4.7	0.85	1.19	2.10
23							36.3	−0.7						0.89		
24							34.9	+0.7						0.82		
25	1,875	32	124	18.7	39.3	30.8	32.5	−1.7		31.6	−0.8	31.5	−0.7	0.67	1.23	1.66
26	625	40	62	10.1	22.3	20.0	19.9	+0.1		17.7	+2.3	17.9	+2.1	0.80	1.21	1.46
27	7,500	44	114	20.0	42.0	29.2	31.2	−2.0	−3.1	33.8	−4.6	33.6	−4.4	0.51	1.12	1.72
28							34.1	−4.9						0.64		
29							31.6	−2.4						0.53		
30	1,000	48	97	18.5	35.0	33.7	29.7	+4.0	+3.6	28.8	+4.9	28.0	+5.7	0.68	1.13	1.63
31							30.5	+3.2						0.73		
32	5,000	56	148	16.8	34.7	24.0	26.3	−2.3		28.0	−4.0	27.8	−3.8	0.53	1.39	
33	5,000	56	104	16.8	34.3	27.4	28.3	−0.9		27.8	−0.4	27.5	−0.1	0.66	1.39	
34	800	60	134	11.5	29.9	19.3	22.2	−2.9		23.0	−3.7	23.9	−4.6	0.58	1.19	1.46

Note: Test values were taken from regular commercial tests and not from special tests. X_l has been calculated by Kilgore's formulas. X_d' has been calculated either by Kilgore's formulas or by a simplified formula. Ratio of pole ampere turns to pole plus tooth ampere turns has been calculated in several cases by more than one method.

Approximate Graphical Method for Calculating X_p

Using these simplifications, then, figure 4 can be reduced to figure 5, and the point A of figure 1, which is the operating point at zero power factor, can be determined as the sum of the ampere turns in the gap (equals NG in figure 5) plus the tooth ampere turns (equals NT in figure 5) plus the pole ampere turns (equals SP in figure 5) plus the effective demagnetizing ampere turns of the armature current (equals $D'A'$ in figure 1). After the point A has been obtained, the determination of X_p can be made by the usual method shown in figure 1.

First Approximation for X_p

The above procedure for calculating X_p is a graphical one. The same procedure can easily be reduced to an approximate formula by considering 2 limiting conditions,

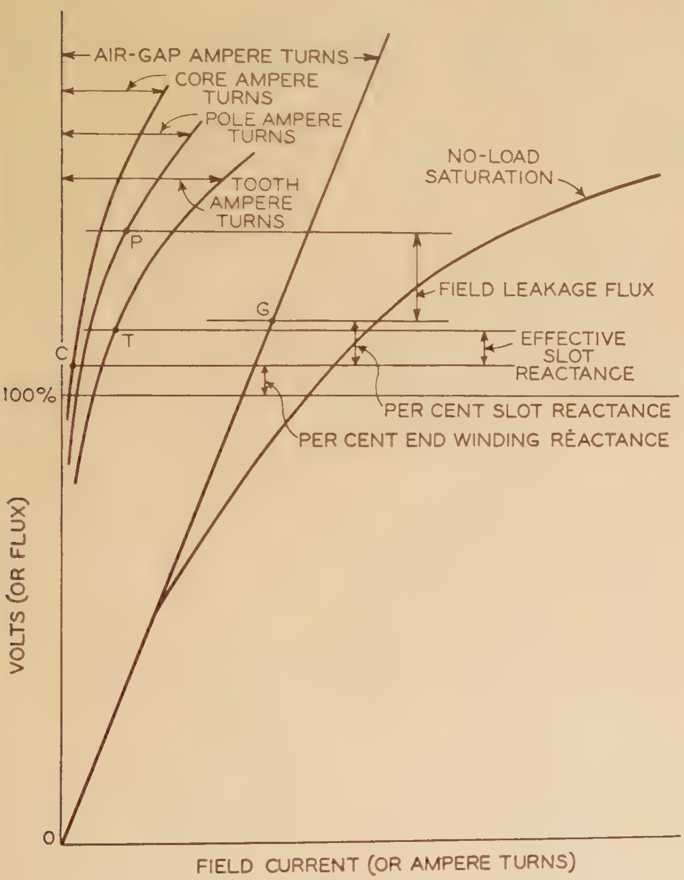


Figure 4. Internal conditions determining X_p

and assuming linear variation between these 2 conditions. The first limiting condition exists when there is no saturation in the poles, all saturation being in the teeth. For this case Potier reactance equals leakage reactance. The second limiting condition exists when all saturation occurs in the poles, and the teeth are unsaturated. For this case Potier reactance equals transient reactance. If intermediate points are assumed to depend directly upon the ratio of pole saturation to total saturation, the formula for X_p becomes

$$X_p = X_l + (X_d' - X_l)\,\frac{\text{pole ampere turns}}{\text{pole plus tooth ampere turns}} \qquad (1)$$

This equation is a simplified form of one given by L. A. Kilgore in his discussion of reference 1.

Second Approximation for X_p

For use where the ratio of pole ampere turns to pole plus tooth ampere turns cannot be determined, an average value for this ratio can be assumed, so that equation 1 becomes

$$X_p = X_l + 0.63\,(X_d' - X_l) \qquad (2)$$

Third Approximation for X_p

In cases where X_l is not available, an empirical formula applicable to average machines has been found to be merely

$$X_p = 0.8\,(X_d') \qquad (3)$$

Comparison of Test and Calculated Results

Results of 34 calculations using formulas 1, 2, and 3 are compared with test in table I, and the same results are shown in graphical form in figures 6 to 9. In figures 7, 8,

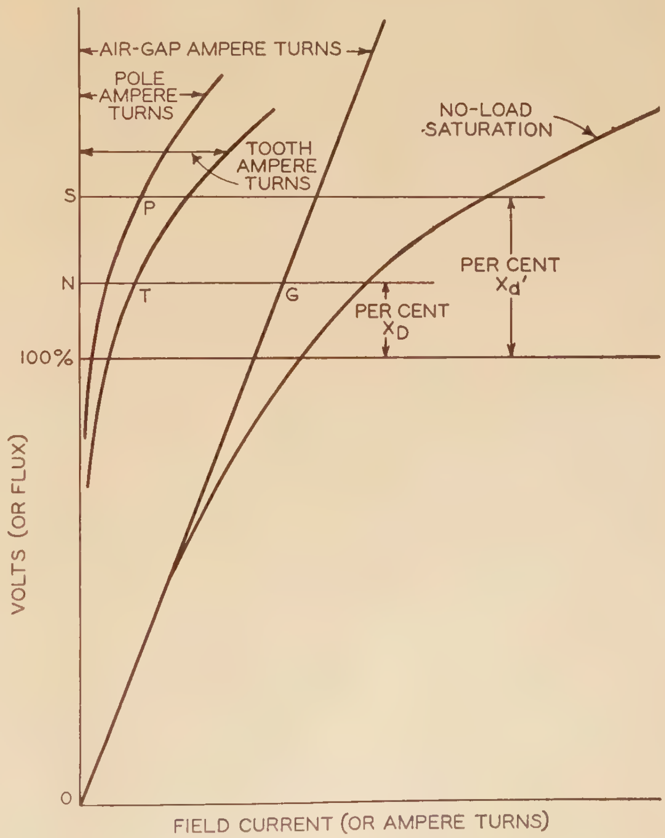


Figure 5. Simplified internal conditions determining X_p

and 9, the difference between test and calculated values for each machine has been drawn as a line above or below a zero axis, and the lines have been arranged in order of descending magnitude to give in effect a distribution curve. The abscissa can consequently be labeled "number of machines exceeding a given per cent error." Thus in figure 8

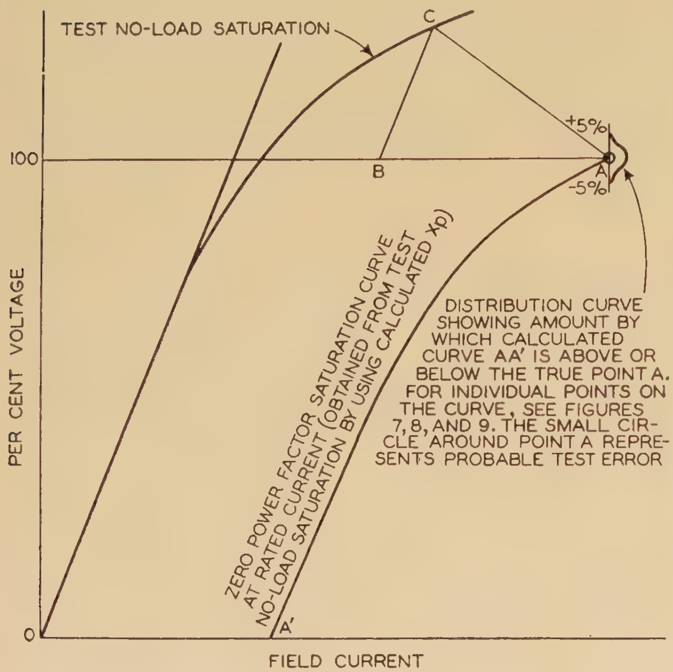


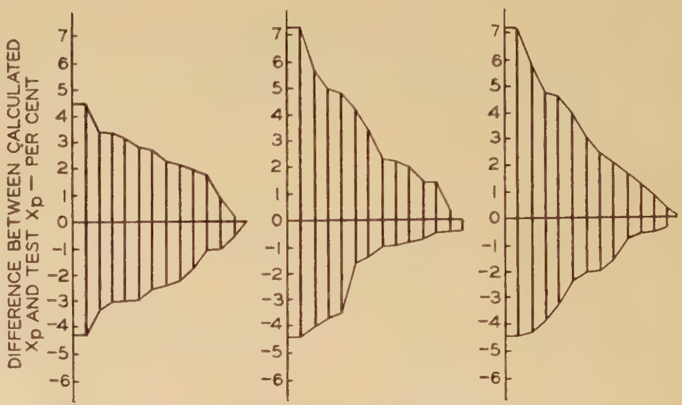
Figure 6. Comparison of calculated X_p with test X_p

the ordinate for -3 per cent error yields an abscissa whose value is 4, which is the number of machines for which test X_p was more than 3 per cent less than calculated X_p. Per cent has everywhere been taken as per cent of rated terminal voltage, in order to avoid confusion and so that the distribution curves of figures 7, 8, and 9 can be more easily visualized in their true significance as per cent of terminal voltage above and below the true point A in figure 6. In this figure, the assumption made is that the no-load saturation curve has been obtained from test, and that calculated X_p is being used to obtain the full load zero power factor curve which will then be above or below the true point A by an amount exactly equal to test X_p minus calculated X_p.

When judging the results, it should be remembered that the quantity being calculated varies with test error and voltage rating as shown in figure 3. Furthermore, the values of end winding leakage reactance and also those of transient reactance as calculated by published formulas differ slightly from each other and from test. The other term in equation 1 is the ratio of pole saturation to tooth plus pole saturation, and it is hardly necessary to say that its value will depend upon the method of calculation used, since all practical methods of calculating saturation in a magnetic circuit as complicated as a synchronous machine involve approximations or empirical factors. In table I, the ratio of pole to tooth plus pole ampere turns for several of the machines has been calculated by 2 or 3 different methods just to show the variation that is likely to be obtained.

In compiling table I, most machines were chosen at random, and the remaining few machines were chosen because they did not check the usual method of calculating saturation. All results have been included in the table, and no machines for which X_p has been calculated have been omitted.

Considerable data have been included in table I just to give a better picture of each machine. Thus the values of K_{nl}, K_p, X_d, and X_p are sufficient to permit virtual reconstruction of the saturation curves, and the division



Figures 7, 8, and 9. Difference between test X_p and X_p calculated by equations 1, 2, and 3, respectively

Note: In these figures, each machine is represented by a line from the zero axis up or down to the proper per cent difference. The lines are arranged from left to right in the order of decreasing magnitude to give, in effect, a distribution curve. These curves are indicated to a more correct scale in figure 6

of saturation between stator and rotor can be determined from the ratio of pole ampere turns to pole plus tooth ampere turns given in column 15.

Comments on the Difficulties of Calculating Accurately Potier Reactance

As mentioned before, Potier reactance is a somewhat fictitious reactance, and consequently the more exact method of calculating it to be discussed below will be quite different from the usual method of calculating a reactance, and will consist only of calculating 2 saturation curves, one under full-load zero power factor conditions, and the other under no-load conditions. Furthermore, since the usual methods of calculating saturation curves are so well known, the following discussion will assume a knowledge of the general method, and will discuss only 3 details that have particular bearing on the difference between the no-load curve and the full current zero power factor curve.

1. At no-load, the flux form in the air gap is shown for a typical machine in figure 10. The estimated effect of saturation on this flux form is shown at 125 per cent

voltage by the dotted curve on the same figure. The flux form constants of these waves are tabulated in the figure. The ratio between the fundamental peak and the actual peak flux is C_1. The ratio of the average to the peak value of the actual flux wave is C_p.

2. Under full current zero power factor conditions, the same curve and its constants are also shown in figure 10. The obtaining of these curves, especially the ones under saturated conditions, may involve considerable cut and try work or else good approximations, but the calculation of tooth and of gap ampere turns is relatively simple once the constants have been obtained. It is assumed that tooth flux and gap flux are identical because, as shown in the appendix, tooth saturation occurs largely at the tips of the teeth. Actually, the flux form changes continuously between the tips and the base of the teeth. In general, the flux forms become flat-topped soon after saturation occurs in the teeth. Saturation in the pole between damper bars or in the pole tips has been neglected, but may be quite important in the occasional machines where it occurs.

3. Having calculated tooth and gap ampere turns by

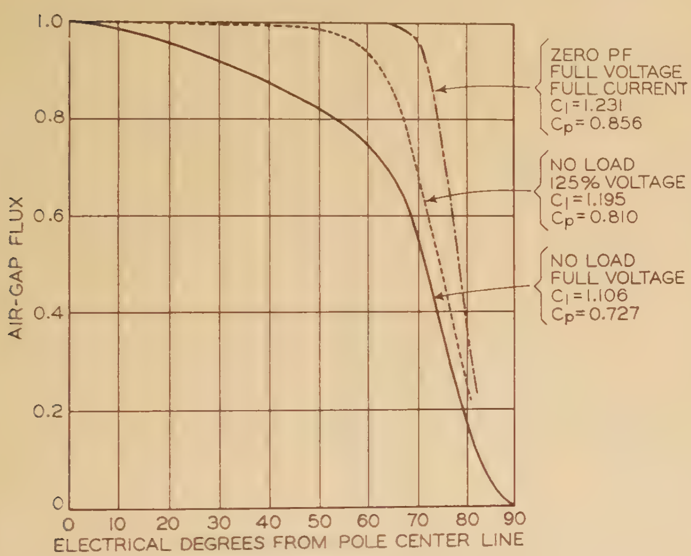


Figure 10. Flux forms for a typical salient-pole machine under different operating conditions

the usual methods, but using the above corrected values of C_1 and C_p, the next step is to calculate pole ampere turns; but in order to do this, the field leakage flux must be obtained. If a constant permeance is assumed in the leakage flux paths between pole sides regardless of the amount of flux or shape of the field, then the leakage flux is this permeance times the number of ampere turns acting, and the per unit leakage is this flux divided by the average flux from figure 10.

For help in approximating the ampere turns acting to produce flux between pole sides, the sketches of figure 11 have been drawn. Two things should be noted: first, that the ampere turns acting between pole heads is practically the sum of the gap ampere turns plus the demagnetizing ampere turns plus the tooth ampere turns—all under the proper conditions of flux form and saturation; second, that the ampere turns acting between the pole sides may sometimes act in a direction that tends to reduce the pole density instead of increasing it. In other words, the leakage flux between pole sides may actually become negative so that the effective permeance between pole sides does not remain constant. This second effect takes place only when the pole saturation becomes an appreciable part of the total ampere turns, but the amount of the effect will always differ between no-load and full load because of demagnetizing ampere turns, and consequently, will affect Potier reactance.

The above 3 items (1. change of wave shape with tooth saturation, 2. change of wave shape with demagnetizing ampere turns, 3. change of pole side leakage flux with pole saturation) are the major ones causing difference between the no-load and full-load saturation curves. Items 1 and 2, for example, cause the air gap ampere-turn line to bend back at higher voltages as shown in figure 12 instead of being the straight line it is often considered to be. Item 3 causes appreciable reduction in pole density at the high voltages and currents where pole ampere turns are greater than gap ampere turns.

It must be remembered in considering the above, that all practical methods of calculating synchronous machine

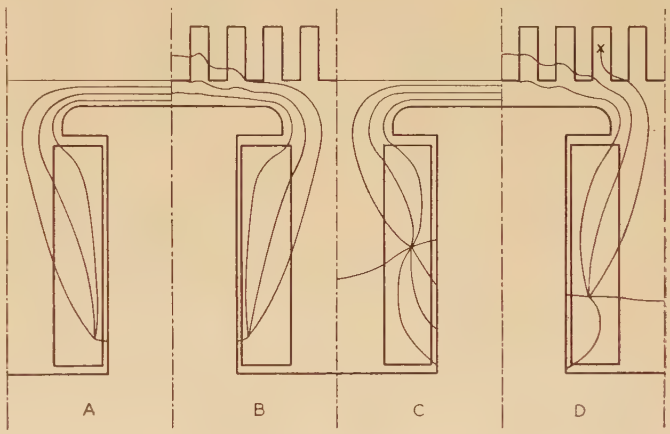


Figure 11. Approximate flux maps for different conditions (ampere turn lines only are shown)

A—No load, no saturation

B—No load, no pole saturation. Tooth ampere turns equal gap ampere turns

C—No load, no tooth saturation. Pole ampere turns equal gap ampere turns

D—Full load, zero power factor. Pole, tooth, gap and demagnetizing ampere turns equal

saturation are approximate, and that the only really exact method is to make flux plots of the entire circuit, including both saturated and unsaturated portions.

Saturation of Potier Reactance

In the preceding analysis, no attempt has been made to show in detail the effect of saturation on X_p. In com-

piling table I, all comparisons have been made arbitrarily at rated voltage and rated current, and the unsaturated value of X_d' has been used. The use of the saturated value of X_d' is not thought to be justified because saturated reactance depends upon $d\phi/dI$, that is, upon rate of change of saturation, while saturated X_p does not.

Symbols

X_d' = direct axis transient reactance
X_p = Potier reactance
X_d = direct axis synchronous reactance
X_l = armature leakage reactance
X_{ad} = direct axis demagnetizing reactance ($= X_d - X_l$)
AT = ampere turns per pole
K_{nl} = ratio of no-load ampere turns to gap ampere turns at 100 per cent voltage
K_p = ratio of no-load ampere turns to gap ampere turns at (100 per cent plus per cent X_p) voltage
C_1 = ratio of fundamental to maximum of air gap flux form
C_p = ratio of average to maximum of air gap flux form

Appendix—Use of Exponential Formula for Saturation Curve

The saturation curve of iron very closely approximates an exponential curve over the usual ranges used in synchronous machines. In figure 13, the ampere turns per inch required by a saturated wedge-shaped tooth are shown for 2 values of maximum density—140,000 and 110,000 lines per square inch. The actual curve and the exponential representation of it have both been drawn in order to show the substantial agreement that exists between them. The total ampere turns required to force the flux from tooth tip to any ordinate of the curve is shown by curve B of the same figure, and is equal to a constant times the integral of curve A. The interesting thing to note is that if the exponential representation is chosen, the curve of total ampere turns (curve B) becomes the usual curve of exponential decay or build up, from which it can be seen that if the wedge-shaped tooth were replaced by a parallel-sided tooth whose length was equal to the distance from the tooth tip to the point where $\frac{\text{tooth width}}{\text{minimum tooth width}} = 1.10$, approximately the same total ampere turns as in the whole wedge-shaped tooth would be obtained.

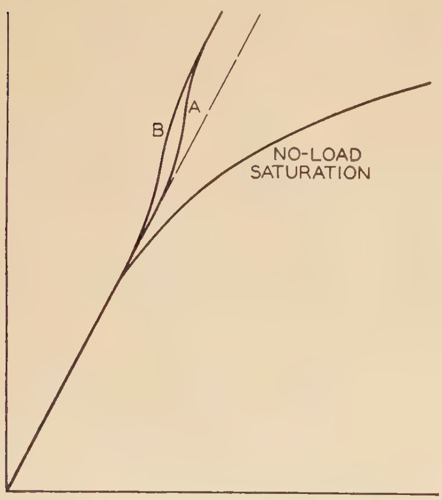


Figure 12. Effect of change of flux form on air-gap line of a typical machine

A—Under no-load conditions

B—Under full-load zero-power-factor conditions

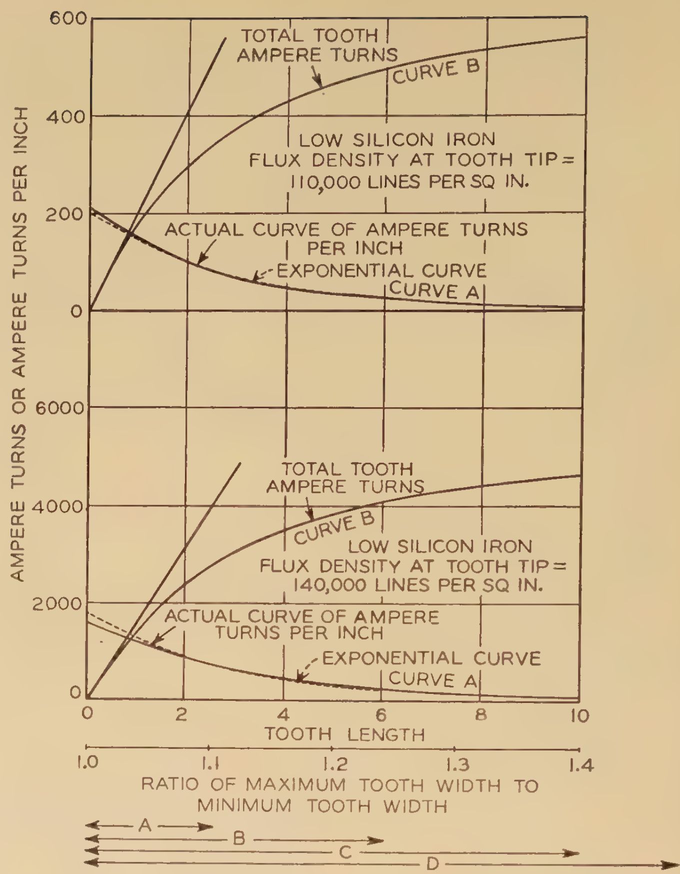


Figure 13. Saturation of a trapezoidal tooth (with 100 per cent air area in parallel)

A—Ratio of maximum to minimum tooth width for average 60-pole machine

B—Ratio of maximum to minimum tooth width for average 20-pole machine

C—Ratio of maximum to minimum tooth width for average 8–10-pole machine

D—Ratio of maximum to minimum tooth width for average 2–4-pole machine

If an exponential equation is used for saturation, then the ratio of tooth to pole ampere turns can be approximated as

$$\frac{\text{tooth ampere turns}}{\text{pole ampere turns}} = \left(\frac{\text{tooth length}}{\text{pole length}}\right)\epsilon^{\frac{0.07\,(\text{tooth density} - \text{pole density})}{1{,}000}} \tag{4}$$

And equation 1 will become:

$$X_p = X_l + (X_d - X_l) \times \frac{1}{1 + \left(\frac{\text{tooth length}}{\text{pole length}}\right)\epsilon^{\frac{0.07\,(\text{tooth density} - \text{pole density})}{1{,}000}}} \tag{5}$$

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Characteristics of the New Station-Type Autovalve Lightning Arrester

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THIS PAPER is a description of the characteristics of a new line of station-type autovalve arresters. These arresters are designed to limit the surge voltage to a low value for all types of surges, and at the same time to have high enough 60-cycle breakdown and cut off characteristics to be practically free from trouble due to transient 60-cycle overvoltages.

The arrester elements are sealed in porcelain weather casings having aluminum-alloy castings cemented to each end. The castings serve to make electrical connection to the arrester elements and to bolt the separate units of a complete arrester together. The autovalve blocks are cemented in the porcelain casing with a hard chlorinated wax which acts as a mechanical support for the blocks and prevents any movement during shipping or erection. The gap assemblies are sealed in porcelain tubes having spun metal caps soldered directly to a band of metallic glaze on the porcelain. The gaps are dried before making the final seal by forcing hot dry air through them for several hours. Figure 1 is a cut-away view showing details of the construction of a 60,000-volt arrester.

In developing this arrester it was found that improvements in protective ratio, 60-cycle breakdown characteristics, and interrupting ability of the gaps could be made by utilizing 2 independent gap structures, each of which was designed for its particular purpose. The 2 gap structures have been called switch gap and quench gap. Normally the switch gap is located at the top, and the quench gap at the bottom of the arrester. In the higher-voltage arresters, the quench gap is in 2 or more units. Each gap unit, together with the proper number of porous blocks, is assembled in a separate casing, as in the lower half of figure 1. The complete arrester is built up of these quench-gap and block units with a switch gap either mounted directly on them or suspended above them.

The quench gap has a high 60-cycle breakdown and power follow interrupting ability, and at the same time a low surge breakdown. The high interrupting ability has been obtained by using a large number of closely spaced gaps. The high 60-cycle and low surge breakdown has been obtained by using a gap element which has an impulse ratio of very nearly unity, and by using a resistance shunt to distribute the voltage evenly across all of the gaps. In figure 2 is shown a unit of 3 gaps assembled inside the molded resistance ring. The low impulse ratio of this type of gap is probably due to the formation of a corona or similar discharge near the points of contact of of the mica washer and the electrode. This discharge furnishes an abundance of ions for the gap, and as a result the gap is very fast and has a low impulse ratio. As a check on this, tests were made in which a ring of Micarta between the outside edges of the electrodes was substituted for the mica washers. Although the gap spacing was the same, the impulse breakdown became erratic and impulse ratios as high as 2 were obtained. In the assembled gap a number of units of 3 gaps and a resistance ring stacked on top of each other are sealed in a porcelain gap tube. The spring spacer between units assures good contact to the resistor and takes up any manufacturing variation in the parts.

The switch gap insulates the arrester from the line voltage and prevents the continuous passage of leakage current through the resistance shunt of the quench gap. This is a multiple gap using pressed-brass electrodes separated by porcelain spacers. Improvement has been obtained in the impulse ratio of these gaps by using a molded insert of granulated carborundum in the face of the electrode. A double-gap element of this type is shown in figure 3. The surface of the insert is slightly below the face of the electrode and the arc takes place between the metal surfaces and not to the surface of the carborundum insert. The chart of figure 4 shows the results of tests on 4 gap assemblies, each composed of 2 gaps, as in figure 3, in series. The 60-cycle breakdown and 10 front-of-wave breakdowns were taken on each gap assembly. Each gap assembly, in series with an autovalve block, was then surged 50 times with a 4,000-ampere surge while connected to a 3,000-volt power source. Then the 60-cycle and impulse tests were repeated. This was continued until a total of 200 power follow shots had been reached In the chart the vertical lines represent the spread in the impulse ratio of a particular gap assembly for 10 tests. The number above each line designates the gap assembly tested. The line in the column at the right shows the spread in impulse ratio of a similar gap assembly without the inserts.

The operation of the dual gap in the complete arrester is as follows: When the surge voltage becomes 50 to 75 per cent above the crest of the arrester rating, the switch gap breaks down and the entire voltage is applied to the quench gap. If the voltage continues to rise, the quench gap breaks down when the voltage reaches 125 to 150 per cent above the crest of the arrester rating. The surge is then discharged through the autovalve blocks which hold the surge voltage to a safe value. After the surge is discharged, the normal-frequency current of approximately 20 amperes crest passed by the autovalve blocks is inter-

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1. For all numbered references, see list at end of paper.

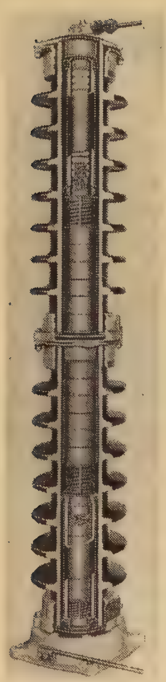


Figure 1 (left). Cut-away view of a 60,000-volt type SV arrester showing details of the internal construction

A—Switch-gap assembly
B—Quench-gap assembly
C—Autovalve blocks

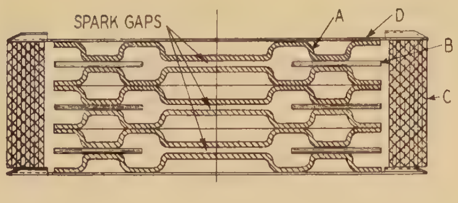


Figure 2. Quench-gap unit consisting of 3 gaps and a shunting resistor

A—Pressed-brass electrode
B—Mica washer
C—Molded ring of resistance material
D—Spring contact plate

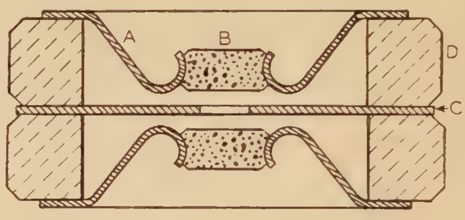
rupted at the first current zero by the quench gap. The leakage current of less than a milliampere passed by the quench-gap shunting resisters is then interrupted by the switch gap.

Figure 5 is a curve of the protective ratio as a function of the time to breakdown of the dual gap on various wave fronts. The time to breakdown was taken as the time from zero to breakdown voltage on an average front taken between the 10 and 90 per cent points. In order to get a common scale for the different ratings, the actual breakdowns in kilovolts were divided by the crest value of the maximum arrester rating in kilovolts. The actual gap breakdown of any particular arrester can be obtained by multiplying the crest of maximum arrester rating by the protective ratio for any time to breakdown. This curve shows how fast the arrester gap is. For example, on the standard rate of rise of 100 kilovolts per microsecond for each 11.5 kilovolts of arrester rating the breakdown occurs in about 0.4 microseconds and the ratio is about 2.4 Even doubling the rate of rise, which means a breakdown in the very short time of 0.2 microseconds, only increases the gap protective ratio to about 2.6.

The autovalve block has a high surge-current-discharge capacity and at the same time a low protective ratio. The protective ratio on the standard 1,500-ampere 10x20 wave is 2.1. This means that for a current of this type the voltage across the arrester elements will be limited to 2.1 times the crest of the arrester rating. In order to compare the protective characteristics of the arrester with the characteristics of insulation to be protected, its performance on various rates of rise of current, as well as crest currents must be known. The results of tests on these blocks at crest currents of 1,500, 5,000, and 10,000 amperes with the rates of rise of currents varying from 300 amperes per microsecond to 10,000 amperes per microsecond are shown in the curves of f gure 6. An idea of the meaning of a current rising at the rate of 10,000 amperes per microsecond can be seen when it is considered that a traveling wave on an open line of 400 ohms surge impedance rising at the rate of 2,000,000 volts per microsecond would be needed in order to produce this rate of rise of current in an arrester connected at the end of the line. These curves strikingly show the flat characteristic of the autovalve block. Even at surge currents of 10,000 amperes and rates of rise of 10,000 amperes per microsecond, the protective ratio is held to the low value of 2.8. These data have been replotted in a more useful form in the curves figure 7. These curves give the protective ratio of the arrester at various surge current for the rates of rise of current of 1,000, 5,000, and 10,000 amperes per microsecond. Since the curves are relatively close together, rates of rise between the values shown can be easily interpolated. From these curves the voltage which will appear across any given arrester for any assumed current wave shape can be easily determined. The protective ratio for any rate of rise and crest current can be determined from the curves. The crest value of the maximum 60-cycle rating of the arrester multiplied by this ratio gives the surge voltage across the arrester.

This arrester can safely discharge surge currents in excess of 50,000 amperes without damaging the arrester. On surge currents of this high magnitude the arrester still offers protection to insulation, as can be seen by examining the oscillograms of figure 8. These oscillograms

Figure 3. Gap elements used in switch gap



A—Pressed-brass electrode
B—Molded insert of granulated carborundum
C—Brass plate
D—Wet-process porcelain spacing ring

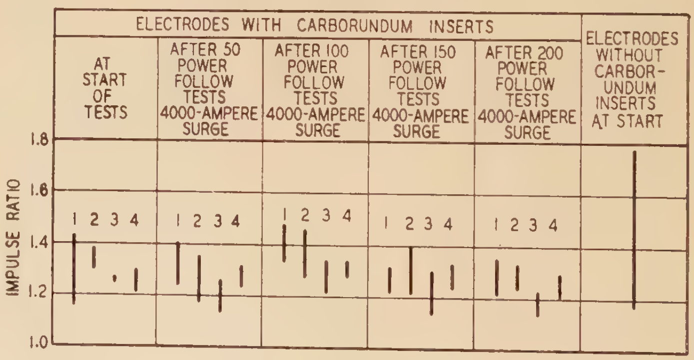


Figure 4. Performance of gaps, as in figure 3, with carborundum inserts

Each vertical line represents the spread in the impulse ratio on 10 successive front wave breakdowns. The numbers above the lines designate the gap tested. The line in the column at the right shows the spread in impulse ratio on a similar gap assembly without the carborundum inserts

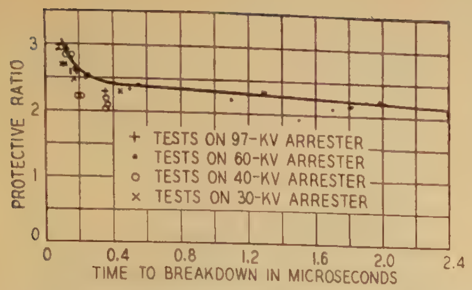
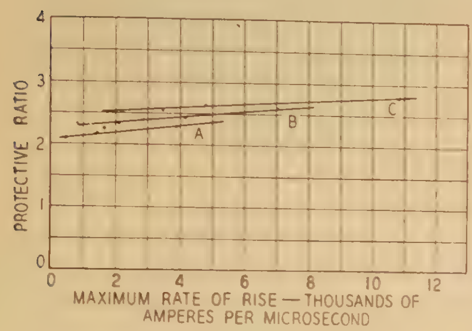


Figure 5. Surge breakdown of the dual gap as a function of the time to breakdown

In order to obtain a common scale for the arresters of different ratings, the actual breakdown voltage was divided by the crest of the rated voltage of the arrester tested. All breakdowns were on the front of the wave. The time to breakdown was taken as the time from zero to breakdown voltage on a line through the 10 and 90 per cent points



A—Crest current of 1,500 amperes
B—Crest current of 5,000 amperes
C—Crest current of 10,000 amperes

Figure 6. Protective ratio of the autovalve blocks as a function of the rate of rise of current for different crest currents

The maximum rate of rise of current was taken as the rate of rise of approximately the first half of the front of the current wave

were taken on 6-kv autovalve block units. Since the characteristics of the autovalve block add directly, tests on single blocks can be extrapolated to any arrester rating.

At its maximum rated 60-cycle voltage the *SV* arrester will pass a power follow current of between 20 and 30 amperes crest. This power follow current is interrupted at the first current zero by the arrester gap. The power follow current is low enough and of such short duration that it will not cause any system disturbances. Power-follow tests have been made on this design of arrester on ratings up to 60 kv, both dry and with a spray to simulate rain. Under no conditions has a failure been produced.

The results of various investigations on the surge current in the direct stroke in this country and abroad, show that the current in the majority of the strokes is below 50,000 amperes, with occasional very heavy strokes where the current reaches magnitudes of the order of 200,000 amperes. Norinder, of Sweden, has made measurements of the rate of rise of current by means of measurements of the magnetic field produced by the stroke, and he reaches the conclusion that in about 65 per cent of these strokes the maximum rate of rise of current is below 6,000 amperes per microsecond. Because of the nature of the instrument used in making these measurements, it is highly probable that a large number of strokes of low current and low rate of rise are not recorded at all, and therefore these data only include the strokes of most severity. Even taking this data as it is, we find that the new type of *SV* arrester will discharge the majority of the currents of direct strokes without damage to the arrester, and the arrester while discharging these high currents will offer a fair degree of protection to connected equipment. A station-type arrester is rarely called upon to discharge the entire current of a heavy direct stroke, because the arrester is normally

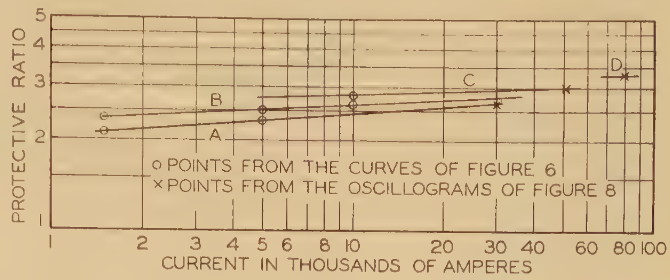


Figure 7. Protective ratio of the autovalve blocks as a function of surge current for different maximum rates of rise of current

A—Maximum rate of rise of 1,000 amperes per microsecond
B—Maximum rate of rise of 5,000 amperes per microsecond
C—Maximum rate of rise of 10,000 amperes per microsecond
D—Maximum rate of rise of 20,000 amperes per microsecond

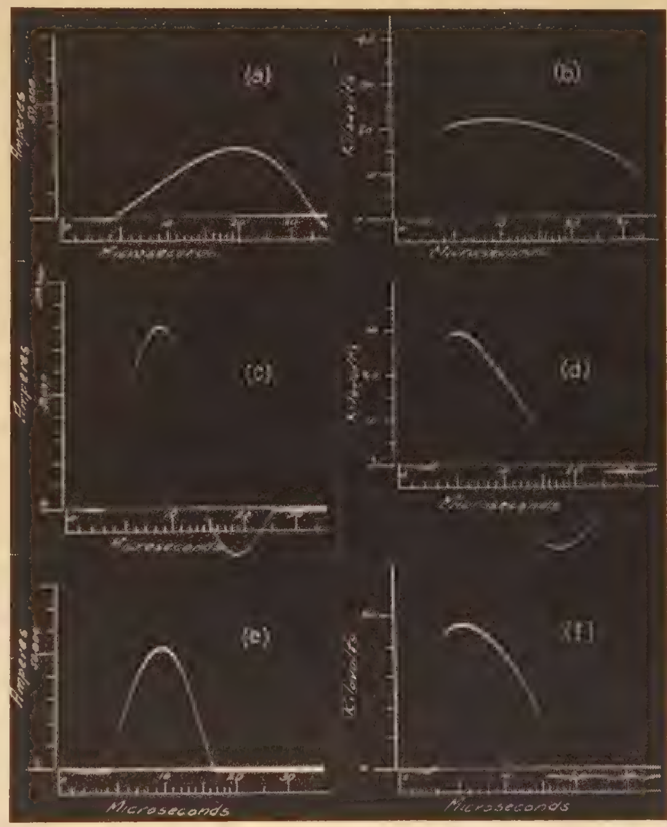


Figure 8. High-current surge tests on autovalve blocks

A, B—Ampere-time and volt-time curves of a 6-kv autovalve block discharging a surge current of 30,000 amperes with a maximum rate of rise of 3,000 amperes per microsecond. The voltage is limited to 22 kv or a protective ratio of 22/6 × 1.41 = 2.6

C, D—A 6-kv block discharging 79,000 amperes—20,000 ampere per microsecond. The crest voltage of 29 kv represents a protective ratio of 3.4

E, F—Two 6-kv blocks in series discharging 53,000 amperes—13,000 amperes per microsecond. The crest voltage of 48 kv represents a protective ratio of 48/(12 × 1.41) = 2.8

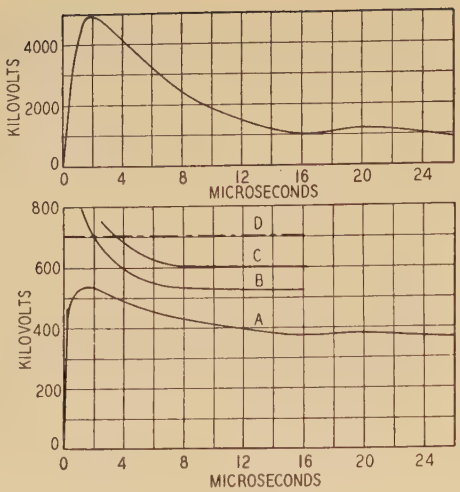


Figure 9a. Retrace of 5,000,000-volt lightning surge recorded on a 115,000-volt wood-pole line in Arkansas

Figure 9b. Performance of a 121,000-volt arrester for 115,000-volt ungrounded neutral service on a surge as in (a). The arrester on the end of a line of 400 ohms surge impedance

A—Voltage across arrester
B—Time-lag curve of $31^1/_2$-inch co-ordinating gap
C—Time-lag curve of 115,000-volt transformer bushing
D—Transformer major insulation, 115,000-volt class

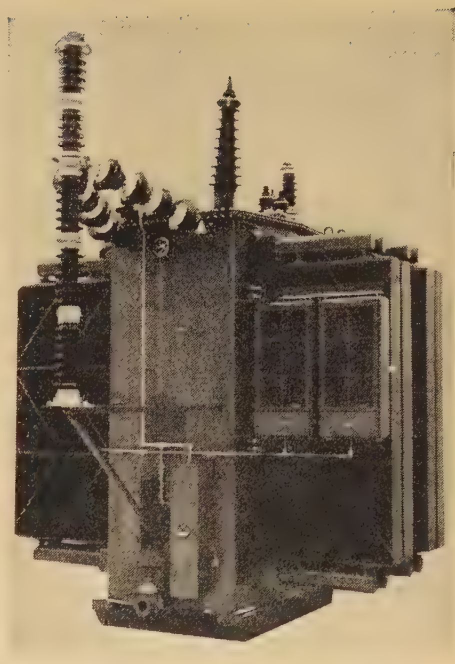


Figure 11. Lightning arresters mounted directly on a power transformer

The arrester for the solidly grounded neutral 132,000-volt primary winding is in the foreground. The top of the arrester for the 46,000-volt grounded neutral secondary can be seen above the secondary bushings

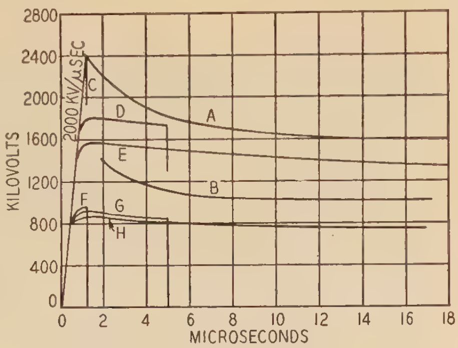


Figure 10. Performance of a 242,000-volt arrester for 230,000-volt ungrounded neutral service on surges entering a station on a steel-tower line of 400 ohms surge impedance insulated with 18 standard insulators

A—Time-lag curve 18 insulators
B—Time-lag curve 64-inch co-ordinating gap
C—Wave chopped on rising front by line insulators
D—Wave chopped at 5 microseconds by line insulators
E—Maximum $1^1/_2$x40 wave passed by line insulators
F—Voltage across arrester for a traveling wave as in *C*
G—Voltage across arrester for wave *D*
H—Voltage across arrester for wave *E*

effectively shielded from direct strokes by the station itself. When heavy strokes occur to the line even in the span next to the station, they will probably cause a flashover of the line insulators, which will offer a parallel path to ground for the lightning currents.

The voltage, and therefore the current, associated with a traveling wave entering a station over the overhead lines is limited by the flashover voltage of the line insulation. It is interesting to analyze the performance of this *SV* arrester for the type of surge which would be expected to enter the station from an overhead line. On a 115,000-volt wood-pole line in Arkansas a cathode-ray oscillogram of a lightning surge was obtained which reached a crest voltage of 5,000,000 volts in slightly less than 2 microseconds and decayed to half value in about 8 microseconds.[1] This is the highest voltage lightning surge that has been recorded on a line. In figure 9*a* a replot of this oscillogram is shown,. Figure 9*b* shows the voltage which would appear across a type *SV* arrester rated at 121,000 volts maximum for ungrounded 115,000-volt application. Assuming a line surge impedance of 400 ohms, the crest current through the arrester would be approximately 24,000 amperes and the rate of rise would be 20,000 amperes per microsecond. The arrester voltage reaches a maximum of about 530 kv. In figure 9 are also shown the time-lag curves of the $31^1/_2$-inch co-ordinating gap and the transformer bushing. The co-ordinating gap has a minimum flashover of about 525 kv and therefore would probably flashover at a relatively long time lag.[2] The arrester voltage is well below the transformer bushing and the transformer major insulation level.[3] In f gure 10 are shown performance curves for a 240-kv arrester applied on a 230-kv ungrounded system in which the line is on steel towers and insulated with 18 standard insulators. The arrester voltage is calculated for a line surge impedance of 400 ohms and a traveling wave rising at the rate of 2,000 kv per microsecond chopped on the rising front, at 5 microseconds, and the maximum full wave passed by the insulators. These voltages are all below the minimum flashover voltage of the 64-inch co-ordinating gap. In both of these examples the arrester for the ungrounded neutral application was used. If the neutral were solidly grounded, arresters rated at 80 per cent of these ratings would normally be used and the margin of protection would be correspondingly better.

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Relay Operation During System Oscillations

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Introduction

THE BETTER relays are made, the better they must be made. This is because better relays enable more economical transmission of power by permitting operation nearer to the stability limits of a system;[1] and the nearer to its stability limits a system operates, the more dependence is placed on its relays.

Relays have often been called superhuman, but they still believe what they see. Reference is made to system oscillations defined here as the oscillating interchange of power between synchronous machines when they hunt or go out of step with one another. Protective relays sometimes mistake these oscillations for short circuits, and trip important transmission lines.[2]

The chance tripping of a sound line is bad at any time. If it happens during hunting, a system might not regain synchronism through its other interconnections. If it happens when generating sources are out of step, a small source might be isolated with a large load, or vice versa. The necessary separation of generating sources on loss of synchronism should be performed by purposely designed relays at prearranged locations. Protective relays should function only for short circuits.[1]

The purpose of this paper is to show wherein a relay's vision is defective and to suggest remedies. We shall first discover what a system oscillation looks like to a relay. Then we shall compare this with short circuits and attempt to find a difference in their appearance. And finally, we shall apply whatever corrective measures are possible.

Characteristics of System Oscillations

In order to simplify the problem, it is assumed that as far as system oscillations are concerned

1. The system can be represented by figure 1
2. All parts of the system always have the same ratio of reactance to resistance, and the impedance of each part is constant
3. The generator voltages behind transient reactance are always equal and constant in magnitude
4. All electrical quantities are referred to the secondary sides of current and potential transformers which transform without change in phase angle

Because the type of system oscillations involved here are balanced 3-phase phenomena, it is sufficient to consider the current of only one phase and its relation to its line-to-neutral voltage as in figure 2. The difference voltage $(V_A - V_F)$ impressed across the total line-to-neutral impedance of the system, causes the current I to flow between the sources. The angle ϕ by which I lags the difference voltage is a constant. As θ changes, the magnitude of I and its angular relation to each of the substation voltages changes. The voltage difference between any 2 points is always a constant proportion of the total difference $(V_A - V_F)$, and hence each vector, which on figure 2 represents a substation voltage, always terminates at a constant division point on the difference voltage. This constant, which defines any location, and which will be called n, is often called the "per unit impedance" from the neutral of source F to the given location.

The following values of n are chosen to locate the various points shown in figure 1.

Point	n
Source F	0
Substation E	0.2
Substation D	0.4
Substation C	0.6
Substation B	0.8
Source A	1.0

For one cycle of slip between the 2 sources, the voltage vector of one source describes a complete rotation with re-

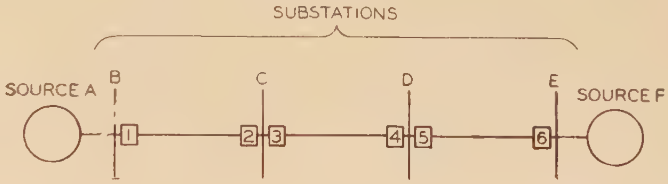

Figure 1. One-line diagram of 3 sections of transmission line connecting 2 generating sources. The numbered rectangles represent circuit breakers arranged to be tripped by protective relays

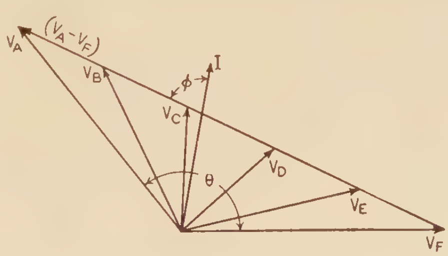

Figure 2. Line-to-neutral voltage and current relations of one phase at the various substations of figure 1 when the voltage V_A back of transient reactance of source A has advanced the angle θ ahead of the corresponding voltage V_F of source F

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1. For all numbered references, see list at end of paper.

spect to the voltage vector of the other source. If only hunting occurs, one voltage swings within a limited sector both sides of the other.

The following equations describe the numerical relations between θ and each electrical quantity affecting relay

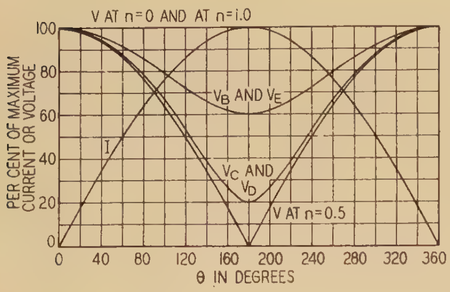

Figure 3. Voltage and current magnitudes at each substation for one complete slip cycle, or for 0 to 360 degrees displacement between the 2 sources

operation. In all of the following discussions, θ will be measured counterclockwise from V_F to V_A.

$$I = \frac{2V_A}{Z'} \sin \frac{\theta}{2} \tag{1}$$

$$V = V_A \sqrt{\cos^2 \frac{\theta}{2} + (1 - 2n)^2 \sin^2 \frac{\theta}{2}} \tag{2}$$

$$\omega = (90 - \phi) + \tan^{-1}\left[(1 - 2n) \tan \frac{\theta}{2}\right] \tag{3}$$

where ω is the angle between V and I. When ω is positive, I leads V.

Z' = total line-to-neutral impedance of the system
V = voltage for any intermediate point

In these and in equations to follow, V_A and V_F may be used interchangeably because they are assumed to be equal in magnitude.

Figure 3 shows how V and I at each station vary with θ, and figure 4 shows the relation between ω and θ when ϕ is assumed to be 75 degrees.

A step toward obtaining a clear understanding of the picture seen by relays is to put the relations of equations 1 and 3 into the form of figure 5. The arrow heads on the curves show the direction in which the head of the current vector moves as θ increases from zero. Current vectors are shown for a value of θ less than 180 degrees. Note that for a given angle, all current vectors have the same length. The curves are symmetrical about an axis inclined at the angle ϕ below the reference axis. The curves for n = 1 and n = 0 are equal circles externally tangent at the origin and centered on the axis of symmetry.

The curve for n = 0.5 is shown dotted. As θ increases, the current increases maintaining a constant angular position with respect to its reference voltage. When θ goes through 180 degrees, the line-to-neutral voltage decreases to zero and reverses, but since this voltage is the reference, the current must be shown as increasing to a maximum and reversing in zero time. What happens to the curve when θ is 180 degrees may be matter for conjecture, but for values of n slightly greater or less than 0.5, the curves approach the dotted circle shown.

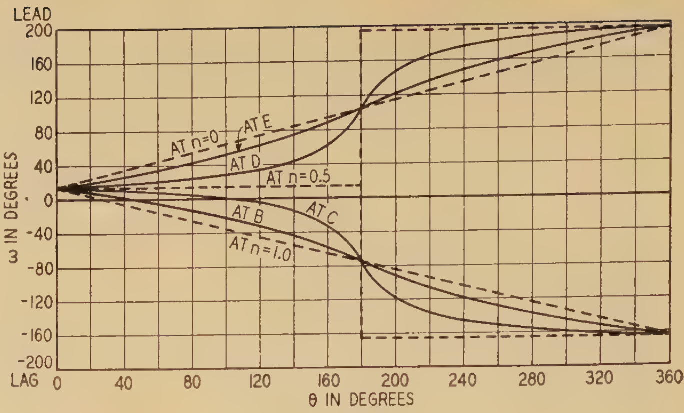

Figure 4. Phase angle between the current and the voltage at each station for one complete slip cycle

The final step in preparing the picture of oscillations as seen by relays is to correct some of the curves of figure 5 by taking into account the point of view of the various relays. Thus far, our picture is one looking down the line from A toward F. The relays connected to trip breakers 1, 3, and 5 are arranged to look in this direction, but the relays at breakers 2, 4, and 6 view the oscillation from the other direction, and to them the current is reversed.

Making the necessary corrections, and separating the curves so as to place each next to the point for which it applies, we have the final picture shown in figure 6. These curves are not expected to show quantitative data, but they have been found invaluable for visualizing the oper-

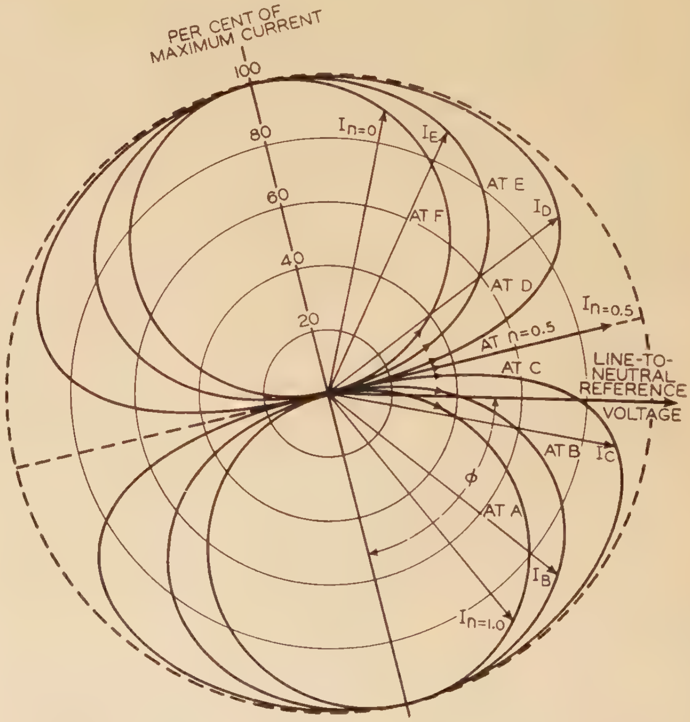

Figure 5. The locus traced by the head of the current vector at each station with respect to the line-to-neutral voltage at the corresponding station for one complete slip cycle. Each locus is lettered to correspond to the station of figure 1 for which it applies

ating tendencies of various relays and for interpreting quantitative data derived from trigonometric analysis.

Operation of a Simple Directional Relay

Because system oscillations are balanced 3-phase phenomena, a polyphase directional relay operates the same as a single-phase relay. Typical operating characteristics of a single-phase directional relay are shown in figure 7 for various voltage magnitudes. The line-to-neutral voltage vector is the reference. For the relay to close its tripping contacts at a given voltage, the current vector for the phase corresponding to the reference voltage must intersect the operating characteristic for the particular voltage as shown by I for 5 per cent of rated voltage. At any given voltage the least current required for operation is that at the angle τ, and hence τ is called "the angle of maximum torque." The least current which will cause operation at normal, or rated, voltage of the relay is called "the minimum pick-up current." This current is shown as I_{MIN}.

The angle of maximum torque is chosen, and the relay is connected, so that the operating region, lying to the right of each characteristic, and extending nearly 90 degrees either side of the angle of maximum torque, will encompass any short-circuit current for which the relay must operate. Generally, the angle of maximum torque is chosen to lie approximately mid-way between the extreme angular positions which the short-circuit current can take for different faults.

If we superimpose the operating characteristic for normal voltage with the proper scale on each of the curves of figure 6, we are provided with an excellent perspective of directional-relay operation during system oscillations. Even though the effect of voltage variation is not shown, the conception gained by this procedure is of much value.

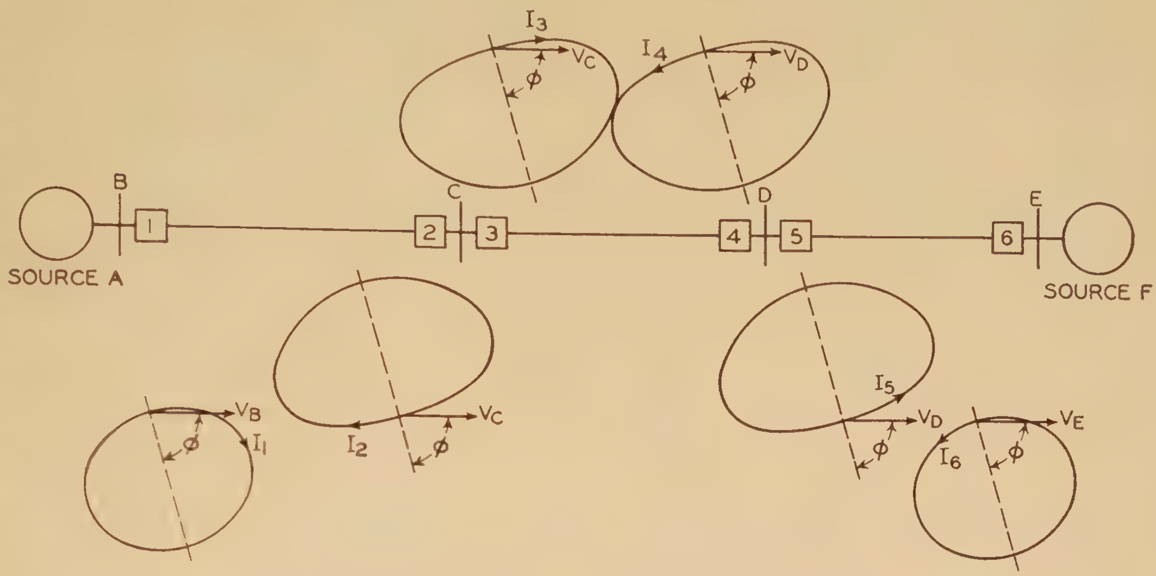

Figure 6. Paths traced by the head of the current vector with respect to its line-to-neutral voltage at each substation for one complete slip cycle. These loci are corrected for current transformer polarity according to the direction in which relays view the current at each station

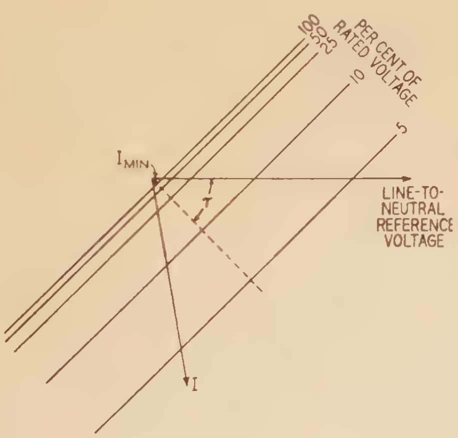

Figure 7. Operating characteristics of a single-phase directional relay, with reference to its line-to-neutral voltage for various voltage magnitudes

In order to obtain quantitative data, it is necessary to resort to an analysis, the result of which is given in the following equation:

$$T = K_1 V_A \left\{ \pm I_{MAX} \left[(2n - 1) \cos (\tau - \phi) \sin^2 \frac{\theta}{2} - \sin (\tau - \phi) \sin \frac{\theta}{2} \cos \frac{\theta}{2} \right] - I_{MIN} \right\} \quad (4)$$

where

T = relay torque; positive torque closes the relay contacts; negative torque opens the contacts
K_1 = a constant
I_{MIN} = the minimum pick-up current of the relay
I_{MAX} = the current which the relay gets when the 2 sources are 180 degrees out of phase

The $\pm$ sign before the first term in the braces is necessary to account for the fact that different relays view a system oscillation in different directions; the + sign applies to relays connected to trip breakers 1, 3, and 5; the − sign applies to relays at breakers 2, 4, and 6.

Equation (4) is general and can be used to determine the operation of a directional relay at any location under any assumed conditions, such as those assumed for figure 8*a*, *b*, and *c*.

Along the abscissa of each curve of figure 8 are the angles by which source A *leads* source F. If source A starts to *lag* source F, we must start at 360 degrees and move to the left in reading the curves. Thus during hunting, if source A leads F and then swings back and goes lagging, we should start from zero degrees and move to the right until which source went leading. If $(\tau - \phi) = -90$ the relays at opposite ends of each line would always have opposite directions of torque which would reverse with no overlap when the displacement went through 180 degrees.

It is evident that all directional relays throughout a system cannot separately be adjusted to preclude the opera-

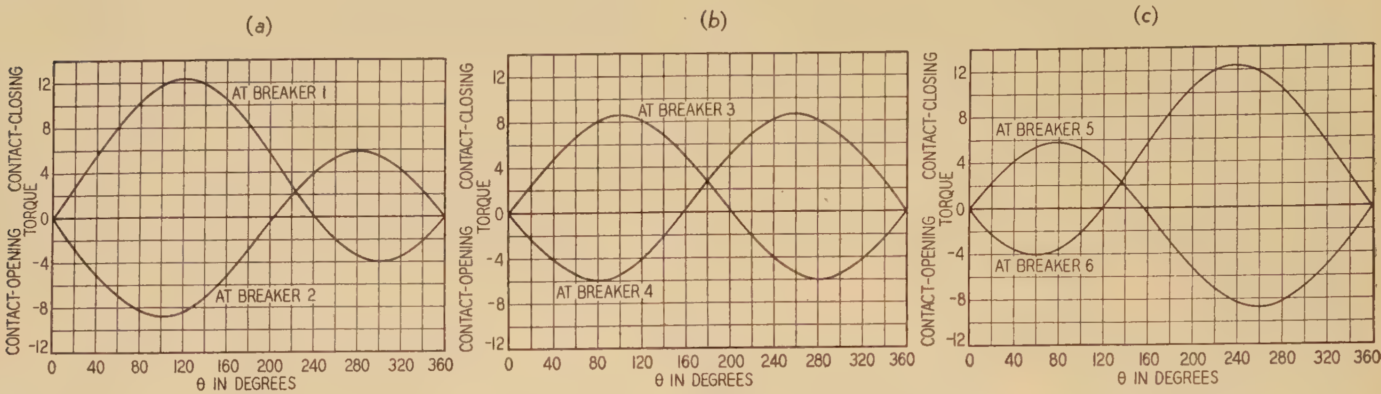

Figure 8. Torque developed in a simple directional relay at each location during one complete slip cycle according to equation 4 with the following assumptions:

$(\tau - \phi) = -45$ degrees. In other words, the angle of maximum torque is 45 degrees leading the natural system phase angle

$I_{MAX} = 20$ amperes $I_{MIN} = 0.1$ ampere

$K_1V_A = 1.0$. This value has no effect on the direction of the torque, but merely on its magnitude

source A begins to swing back; then we must retrace our path to zero, start from 360 degrees, and move to the left as A goes lagging, etc.

The curves of figure 8 show that for small displacement angles between the oscillating sources, the directional relays which face in the direction from the leading to the lagging source immediately close their tripping contacts, while the relays facing in the other direction have the opposite tendency. Thus, in the early stages of an out-of-step oscillation, the relays think that there is a short circuit at the lagging end of the system. As the swing progresses, there comes a time when the relays at both ends of a line perceive a flow of current as to a short circuit in the line which they protect. This condition occurs first for a section of line nearest the lagging end, and then progresses successively through each line toward the leading end as the displacement angle increases further. And finally, as the displacement widens still more, the end which had been leading becomes lagging, and the apparent short circuit passes on toward that end.

During hunting the apparent short circuit moves in from one end, retreats, moves in from the other end, retreats, etc. If the swing is not severe, only the end sections of line alternately may seem to contain a short circuit.

The assumed value of $(\tau - \phi)$ for figure 8 is representative of most relay applications. The limiting values which $(\tau - \phi)$ may have are zero and -90. For the former, there would be danger of failure of the relay to operate for arcing faults near the relay location, and for the latter, the relay might operate sluggishly on highly lagging short circuit current. If $(\tau - \phi) = 0$, the relays at breakers 2 and 5 would never close their tripping contacts, while the relays at breakers 1, 3, 4, and 6 would always close their contacts regardless of the displacement or of tion of some of them during system oscillations. Since other types of relays are invariably used with directional relays, we must of course examine their characteristics too before drawing conclusions as to the over-all operation of any protective scheme.

Operation of Directional Relays With Voltage Restraint

A directional relay with voltage restraint is a simple directional relay which is given an impedance characteristic, or a voltage restraint, for current flow in its tripping direction. The operating characteristics of such a relay are shown in figure 9. It will be noted that the minimum pick-up current I'_{MIN} is a maximum at normal, or rated, voltage, and as the voltage decreases the pick-up current decreases. However, at very low voltages where the restraint becomes negligible, the pick-up current increases the same as for a simple directional relay; to avoid confusion, this is not shown on figure 9.

The superposition of this operating characteristic on the curves of figure 6 would have much the same appearance as for the simple directional relay. It is obvious, however, that the voltage restraint will render this relay less sensitive to oscillations.

An analysis of the operating tendencies of a directional relay with voltage restraint provides the following torque equation:

$$T = K_1V_A\left\{\pm I_{MAX}\left[(2n-1)\cos(\tau-\phi)\sin^2\frac{\theta}{2} - \sin(\tau-\phi)\times \sin\frac{\theta}{2}\cos\frac{\theta}{2}\right] - I_{MIN} - (I'_{MIN} - I_{MIN})\left[(1-2n)^2\sin^2\frac{\theta}{2} + \cos^2\frac{\theta}{2}\right]\right\} \quad (5)$$

where T and K_1 have the same meanings as for equation (4) and where:

I_{MIN} = the minimum pick-up current of the relay if the voltage restraint is removed

I'_{MIN} = the minimum pick-up current of the relay with voltage restraint

The significance of the ± sign before the first term of equation 5 is the same as for equation 4.

Curves illustrating relay operation according to equation 5 are given in figures 10*a*, *b*, and *c* The effect of the voltage restraint is largely to move the curves of a simple directional relay bodily toward the nontripping region. This effect is more pronounced for small displacement angles for which the voltage restraint is relatively high. As the voltage decreases with increasing displacement, the curves approach those of the simple directional relay more closely the nearer the relay is to the impedance center of the system. The curve for a voltage-restrained directional relay at the impedance center would converge to the curve of a simple directional relay at θ = 180 degrees.

The voltage restraint chosen for the curves of figure 10*a*,

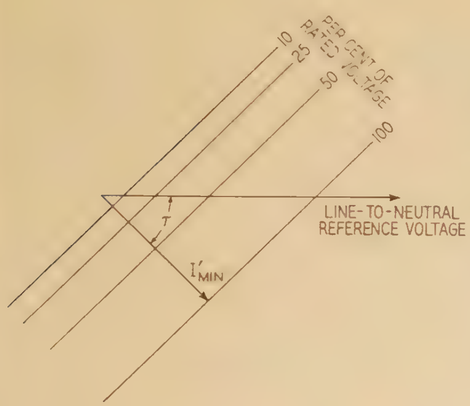

Figure 9. Operating characteristic of a directional relay with voltage restraint, referred to its line-to-neutral voltage, for various voltage magnitudes

b, and *c* does not prevent incorrect relay operation for the assumed conditions during out-of-step system oscillations. It is natural to inquire if, by a better choice of the restraint, operation can be prevented. If we revert to figures 8*a*, *b*, and *c* and read the contact closing torque of a relay without restraint for any given displacement angle, we can equate this torque to the last term of equation 5 which gives the voltage-restraint torque, and hence find a value of I'_{MIN} to reduce the total torque to zero. This value of I'_{MIN} will vary with the displacement angle, and several trials will be necessary to find the proper value so that at no angle does the curve go positive.

The result of such a study is tabulated below:

For No Operation During System Oscillations: For the Relay at Breaker	I'_{MIN} Must Be	Relay Current and Voltage for a Fault at Distant End of Line: I	V	Relay Pick-up for the Fault: $I_{p.u.}$
1	28.2 amperes	25 amperes	0.5 V_A	20 amperes
2	13.7 amperes	12.5 amperes	0.25 V_A	4.9 amperes
3	79.0 amperes	16.7 amperes	0.33 V_A	37 amperes
4	79.0 amperes	16.7 amperes	0.33 V_A	37 amperes
5	13.7 amperes	12.5 amperes	0.25 V_A	4.9 amperes
6	28.2 amperes	25.0 amperes	0.5 V_A	20 amperes

The crucial test of the adjustment is that a relay must operate for faults in the line it protects. Hence, the tabulation lists also the fault current and voltage each relay will have for a fault at the distant end of its line, together with the pick-up current of the relay for the fault voltage. This pick-up current is obtained as follows:

$$I_{p.u.} = \frac{(I'_{MIN})\,(\text{per cent } V_A)}{100}\left[\frac{1}{\cos(\tau - \phi)}\right]$$

where we have assumed $\cos(\tau - \phi) = \cos(-45) = 0.707$.

The tabulation shows that if I'_{MIN} is made large enough, all but the relays at breakers 3 and 4 can be prevented from operating during oscillations without preventing operation for faults because, except for the relays at breakers 3 and 4, $I_{p.u.}$ is always less than the fault current. It is impossible to correct for the misoperation of the relays at breakers 3 and 4 because the line they protect spans the impedance center of the system. When the 2 oscillating sources are 180 degrees out of phase, conditions at these relays are the same as for a dead 3-phase fault at the impedance center of the system which falls in the line between breakers 3 and 4. Hence, if the relays there are to operate for a 3-phase fault in the middle of their line, they cannot be prevented from operating when the oscillating

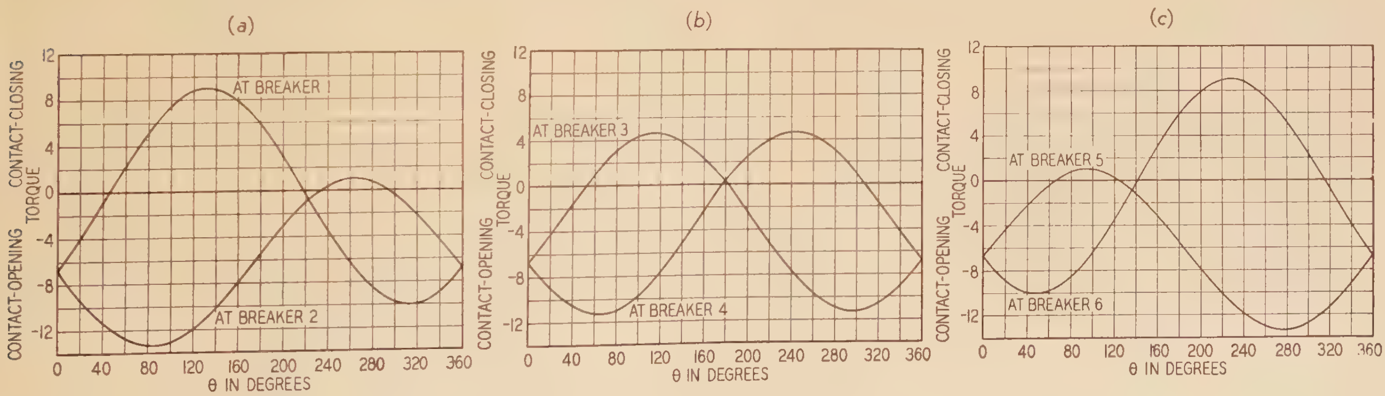

Figure 10. Torque developed in a directional relay with voltage restraint at each location during one complete slip cycle according to equation 5 with the following assumptions:

$(\tau - \phi) = -45$ degrees $\quad I_{MAX} = 20$ amperes $\quad I_{MIN} = 0.1$ ampere $\quad I'_{MIN} = 7.0$ amperes $\quad K_1V_A = 1.0$

sources go through the 180-degree-out-of-phase position.

Since the angle of maximum torque also affects the operation of the relay, let us examine the effect of varying it. Was the choice of $(\tau - \phi) = -45$ the best possible? Considering only the relay at breaker 1, an analysis of its operation provides the following typical data concerning the value of I'_{MIN} necessary to prevent operating during oscillations, and the pick-up current of the relay for faults at the distant end of its line, for values of $(\tau - \phi)$ either side of 45 degrees:

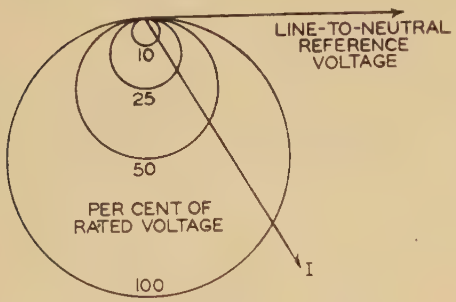

Figure 11. Operating characteristic of a reactance element, with respect to its line-to-neutral voltage for various voltage magnitudes

$(\tau-\phi)$	I'_{MIN}	$I_{p.u.}$
−35.0 deg	30.0 amp	18.3 amp
−45.0 deg	28.2 amp	20.0 amp
−55.0 deg	26.1 amp	22.7 amp

These data indicate that as $(\tau - \phi)$ is reduced, the required I'_{MIN} increases, and the pick-up current for the fault decreases. However, the particular fault considered provides highly lagging current. If the fault current should be more nearly in phase with the relay voltage, the pick-up current for that type of fault would increase when $(\tau - \phi)$ is reduced below −45 degrees. Similarly, as $(\tau - \phi)$ is increased, $I_{p.u.}$ for the highly lagging fault increases. The optimum value of τ is midway between the extreme angular positions which can be taken for the fault at the distant end of the line. For most lines this value of τ will probably lie between 45 and 85 degrees.

In the foregoing discussions concerning the choice of I'_{MAX} and $(\tau - \phi)$, the attempt was made to prevent operation when the oscillating sources went out of step. The problem is obviously simpler if hunting only is considered. It is probable that, by proper adjustment, even the relays protecting a line which spans the impedance center could be restrained against operating during hunting.

These are not general conclusions, but they provide an indication of a possible solution to the problem for some cases. Where a long line exists whose impedance is a more sizeable portion of the total system impedance, it may be found impossible to adjust the relays to select between faults and severe oscillations. Similarly, it may be impossible to use a relay for back-up protection in the case of faults in adjoining lines if the relay is too highly restrained against improper operation during oscillations. And finally, we do not always have the ideal system setup, assumed for the purpose of analysis, where the location of the impedance center never changes, and where the oscillation is not accompanied by the short circuit which causes it. A general conclusion is that while in most cases the majority of voltage-restrained directional relays can probably be adjusted to improve their selectivity between faults and system oscillations, such adjustment is a satisfactory palliative, but not a complete cure.

Operation of a Reactance Relay[2]

This discussion will be confined to the reactance element of a distance relay. Such an element responds properly only to lagging current in a given direction, and consequently it is always used in conjunction with a voltage-restrained directional element which prevents tripping except when a short circuit in the proper direction is indicated.

The operating characteristics of a reactance element are shown in figure 11. For a given voltage magnitude, such as 100 per cent, any current vector I, whose head lies outside of the characteristic circle for the chosen voltage, will cause the element to close its tripping contacts; the element will not operate for any current vector which falls within the circle.

The superposition of this characteristic on each of the curves of figure 6 will indicate that the element is more than likely to operate. In order completely to determine the appearance of an oscillation to a reactance element, the following equation has been derived:

$$X = \pm \frac{Z'}{2}\left[(2n-1)\sin\phi - \cot\frac{\theta}{2}\cos\phi\right] \qquad (6)$$

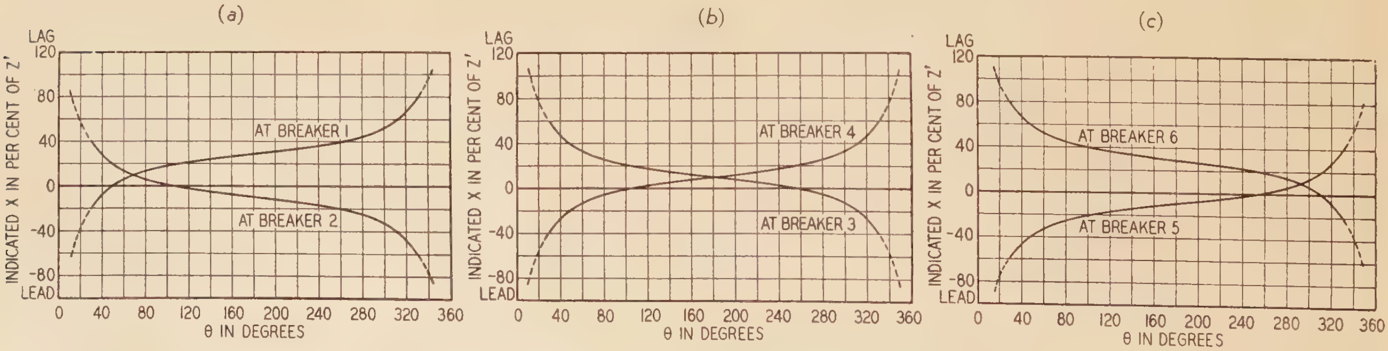

Figure 12. Reactance indicated to a reactance element during one complete slip cycle. The element operates when the indicated reactance is less than a given positive value for which it is adjusted

where X = the reactance indicated to a relay; positive reactance means lagging current; negative reactance means leading current.

The + sign before the right-hand side of equation 6 is to be used for the relays at breakers 1, 3, and 5; the negative sign is for the relays at breakers 2, 4, and 6.

Curves according to equation 6 are shown in figure 12*a*, *b*, and *c*, for which it was assumed that $\phi = 75$ degrees.

In order to use figure 12 to determine relay operation, it is first necessary to establish a value of reactance for which the relay shall operate for faults. A distance relay having a stepped distance-time characteristic is adjusted to operate instantly on its lowest reactance setting for faults up to about 90 per cent of the length of the protected line; the second reactance setting is to provide operation for faults up to about 50 per cent of the length of an adjoining line; the reach of the relay on its third time step is determined solely by the reach of the directional unit.

Each line section of the system shown in figure 1 has a reactance of 20 per cent of the total system reactance. With ϕ assumed to be 75 degrees, 20 per cent of the system reactance is 19 per cent of the system impedance. The setting of the first reactance step will be approximately 17 per cent, and the second step 26 per cent, of the system impedance. This is equivalent to drawing horizontal lines on figure 12*a*, *b*, and *c* at heights of +17 per cent Z' and +28 per cent Z'. The reactance elements will operate for all portions of the curves below these horizontal lines.

Figure 12 shows that the reactance elements at one end, and possibly both ends, of any line are likely to operate on hunting oscillations and that if out-of-step occurs, all elements will operate. It is evident, therefore, that the operation of the voltage restrained directional element will largely determine if tripping will occur. The time, or the reactance step, responsible for tripping would depend on the relay location and on the period and severity of the oscillation. The longer the time delay setting for the second and third steps, the less likelihood there is of operation. It is impossible to generalize except on the basis that if the voltage restrained directional element operates, tripping is possible.

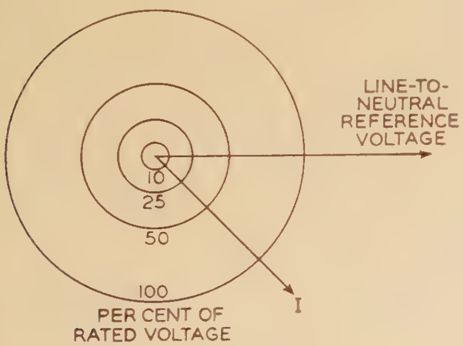

Figure 13. Operating characteristic of an impedance relay, with respect to its line-to-neutral voltage for various voltage magnitudes

Operation of an Impedance Relay[2]

The operating characteristics of an impedance relay are illustrated in figure 13. This relay operates to close its tripping contacts when the head of the current vector lies outside of the circle for any given voltage, such as the current I for 100 per cent of rated voltage. The superposition of this characteristic on the curves of figure 6 will indicate an increasing tendency to operate as the system displacement approaches 180 degrees.

More definite conclusions are possible based on the following equation:

$$Z = \frac{Z'}{2}\sqrt{(1-2n)^2 + \cot^2\frac{\theta}{2}} \tag{7}$$

where Z = the impedance indicated to a relay.

The operation of an impedance relay according to equation 7 is illustrated in figure 14. Conventional distance relays employing impedance elements have 3 such elements, one for each of the 3 distance-time steps. The first step covers about 90 per cent of the protected line, the second step reaches to about 50 per cent of the next adjoining line, and the third step extends to about 25 per cent of the third line section. For use with figure 14, these 3 adjustments may be taken, respectively, as 18 per cent, 30 per cent, and 45 per cent, of Z', the total system impedance. Horizontal lines through these impedance values reveal the operating tendency of the elements.

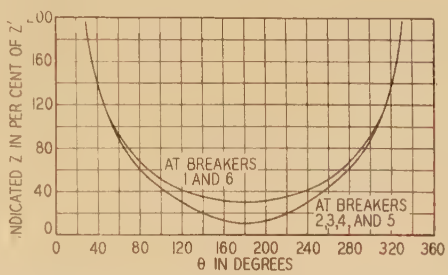

Figure 14. Impedance indicated to an impedance relay during one complete slip cycle. The relay operates when the impedance is less than a given value for which it is adjusted

For the assumed system, figure 14 indicates that operation of only the third step impedance elements at the end stations is likely to occur. All 3 impedance elements at the other stations will function depending on the amount of displacement. Here, as in the case of the reactance relay, a determination of which elements can cause tripping depends on their time settings and on the magnitude and the period of the oscillation. Since conventional distance relays having impedance elements employ an unrestrained directional element, the probable operation of such relays is almost solely determined by the operation of their impedance elements.

Operation of Current and Voltage Relays

The curves of figure 3 are suitable for determining the operating tendencies of simple current or voltage relays. Only the use of time delay in the operation of such a relay can prevent it from closing contacts when its operating point is reached during an oscillation. It is desirable that the resetting time of such relays be as short as possible, else there will be a tendency for the contacts to "notch"

closed during continued oscillations. Incidentally, this quick resetting characteristic is desirable in any relay.

Preventing Tripping During System Oscillations

The preceding analyses show that conventional relays are not individually endowed with enough discriminative ability to distinguish infallibly between any short circuit and any system oscillation. At various instants during oscillations, the electrical quantities affecting relay operation are identical to those existing during short circuits. Are there any differences between the characteristics of oscillations and of short circuits whereby discrimination can be made?

Fortunately, relays commonly used for protecting against ground faults are not affected by system oscillations. Such relays are energized with zero-phase-sequence current and voltage which are not produced by system oscillations. On the other hand, interphase faults not involving ground do not produce zero-phase-sequence quantities. Consequently, ground relays alone will not solve the problem unless protection only against faults involving ground is considered sufficient as a first line of defense.

The consideration of ground relays and the zero-phase-sequence quantities suggests the possibility of using the negative phase sequence current and voltage. System oscillations of the type considered are balanced 3-phase phenomena and hence contain only positive-phase-sequence current and voltage. Since interphase faults, except those which are balanced 3-phase, produce negative-phase-sequence quantities, this characteristic could be used for discrimination. However, there are those who will consider it heresy in view of the fact that balanced 3-phase faults have been known to occur. Barring the accidental closing in of a line on protective grounding devices which lineman have forgotten to remove, there are exceedingly few substantiated cases of short circuits originating in the balanced 3-phase state. Present-day high-speed relays would require an unbalance for only a short time in order to cause tripping. The protection against faults due to failure to remove grounding devices, however, is an easily solvable problem since these faults originate the instant the line breaker is closed. Auxiliary means could be used during that period to permit tripping even though the fault were balanced 3-phase.

The requirement that there be an unbalance in current between the 3 phases in order to permit tripping has been used as a first line of defense measure against short circuits for several years by one large power company with apparently satisfactory results.[3] This method is somewhat different from using negative-phase-sequence quantities since it employs the line currents directly, but it is a simpler and easier method to apply. Its additional shortcoming is that it may in some cases permit tripping for oscillations which accompany external faults. When an unbalance is required for tripping, the remote possibility of balanced 3-phase faults is anticipated by the use of back-up relays having long enough time settings to prevent operation on oscillations alone.

The use of time delay in a relay's operation is perhaps an obvious way to prevent tripping during oscillations. This solution will apply to a back-up relay particularly if the resetting time of the relay is short.

But there are other uses which can be made of the time variable. An important difference between faults and oscillations is that whereas the electrical quantities present during an oscillation may reach proportions identical to those during short circuits, the approach to, and the departure from, the identical state during an oscillation is different on a time basis from that accompanying short circuits. The earliest known appreciation of the possibilities residing in this fact is recorded in a proposed method[4] to prevent the operation of distance relays during hunting following the occurrence of a distant short circuit. There, the distance relay operated very sensitively for a limited time after the occurrence of the short circuit, but before the oscillation could progress far enough to cause false operation, the relay changed its sensitivity so as to be inoperative during the ensuing hunting.

An extension of the principles involved led to making present-day carrier-current pilot relaying immune to any type of system oscillation whether it be accompanied by a short circuit or not.[5] This method of protection uses directional and associated relays at the ends of a line and a simple carrier-current telegraph channel to apprise one end of what is happening at the other. During any system disturbance, if current flows *out* of one end of the line as to an external short circuit, the directional relay at that end permits a carrier-current signal to be impressed on the line which prevents tripping at the other end where the current flow is in the tripping direction.

Reverting to the description of operation of directional relays, it will be recalled that a system oscillation first has the appearance of an external short circuit beyond one end, followed by the appearance of an internal short circuit, and still later appearing again as an external short circuit. This sequence of events in the cycle of an oscillation before and after it resembles an internal fault is used to prevent tripping during that limited period when an internal fault seems to exist. This is accomplished by prolonging the carrier-current signal once it has started during a 3-phase disturbance, for a definite time after the directional relay attempts to stop it, thereby temporarily taking control from the directional relays until they have passed through the period of delusion and once more regain their sense of direction.

This solution to the problem is particularly significant because it is achieved with equipment which is both faster and more selective than any other type having comparable application. The irony of the solution is that we have not bettered the vision of a single relay, but have actually introduced a blinder against its seeing that which it should not.

Conclusions

The content of this paper cannot be fairly revealed by a set of conclusions. The paper was written to be read and studied by those who wish to understand better why

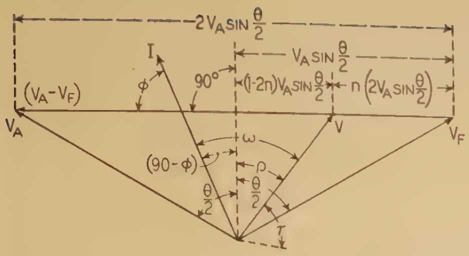

Figure 15

conventional relays operate as they do during system oscillations. An attempt has been made to present the analysis in an easily understandable form which has been found in actual practice to give a better insight into the apparent vagaries of relay operation.

Certain definite conclusions can be drawn (probably more or less obvious without the preceding analyses):

1. Any of the conventional relays except the zero-phase-sequence type is apt to operate in an undesirable manner during system oscillations. This is no reflection on the relay in so far as it reacts as it is intended under definite imposed conditions. The difficulty is that the conditions imposed by oscillations are the same to a single relay's perception as those during short circuits

2. It is possible to adjust some relays to better their discrimination between faults and oscillations depending on a relay's location and on the severity of the oscillation

3. Time delay and quick resetting in a relay's operation are aids toward preventing incorrect operation during oscillations

4. The problem is easily solvable if the best possible protection against balanced 3-phase faults is not required

5. Pilot protection using a wired pilot or carrier current can be made immune to the effects of system oscillations

Appendix

Derivation of Equation 1

If Z' = total system line-to-neutral impedance,

$$I = \frac{(V_A - V_F)}{Z'}$$

From an inspection of figure 15,

$$(V_A - V_F) = 2V_A \sin\frac{\theta}{2}$$

Therefore,

$$I = \frac{2V_A}{Z'}\sin\frac{\theta}{2} \tag{1}$$

Derivation of Equation 2

From an inspection of figure 15,

$$V\cos\rho = V_A\cos\frac{\theta}{2}$$

$$V\sin\rho = (1-2n)\,V_A\sin\frac{\theta}{2}$$

Squaring both sides of these equations and adding,

$$V^2 = V_A^2\left[\cos^2\frac{\theta}{2} + (1-2n)^2\sin^2\frac{\theta}{2}\right]$$

Therefore,

$$V = V_A\sqrt{\cos^2\frac{\theta}{2} + (1-2n)^2\sin^2\frac{\theta}{2}} \tag{2}$$

Derivation of Equation 3

In figure 15,

$$\omega = (90-\phi) + \rho$$

From inspection,

$$\tan\rho = \frac{(1-2n)\,V_A\sin\frac{\theta}{2}}{V_A\cos\frac{\theta}{2}} = (1-2n)\tan\frac{\theta}{2}$$

Therefore,

$$\omega = (90-\phi) + \tan^{-1}\left[(1-2n)\tan\frac{\theta}{2}\right] \tag{3}$$

Derivation of Equation 4

Referring to figure 15, and neglecting the effects of saturation in magnetic circuits of a directional relay, its torque may be expressed as

$$T = K_1 IV\cos(\tau+\omega) - K_2$$

where K_1 is a constant for the production of electrical torque, and K_2 is a constant representing the torque of the control spring.

At minimum pick-up the torque is zero.

$$0 = K_1 I_{MIN} V_A - K_2 \qquad K_2 = K_1 I_{MIN} V_A$$
$$T = K_1[IV\cos(\tau+\omega) - I_{MIN}V_A]$$

Developing this equation,

$$T = K_1\left\{-IV[\sin(\tau-\phi)\cos\rho + \cos(\tau-\phi)\sin\rho] - I_{MIN}V_A\right\}$$

But

$$I = \frac{2V_A}{Z'}\sin\frac{\theta}{2} = I_{MAX}\sin\frac{\theta}{2} \qquad V\cos\rho = V_A\cos\frac{\theta}{2}$$

and

$$V\sin\rho = (1-2n)\,V_A\sin\frac{\theta}{2}$$

Substituting in the torque equation,

$$T = KV_A\left\{I_{MAX}\left[(2n-1)\cos(\tau-\phi)\sin^2\frac{\theta}{2} - \sin(\tau-\phi)\sin\frac{\theta}{2}\cos\frac{\theta}{2}\right] - I_{MIN}\right\} \tag{4}$$

Derivation of Equation 5

The torque of a directional relay with voltage restraint may be expressed:

$$T = K_1[IV\cos(\tau+\omega) - I_{MIN}V_A] - K_3V^2$$

At minimum pick-up the torque is zero.

$$0 = K_1V_A(I'_{MIN} - I_{MIN}) - K_3V_A^2$$

$$K_3 = K_1\frac{(I'_{MIN} - I_{MIN})}{V_A}$$

$$T = K_1\left[IV\cos(\tau+\omega) - I_{MIN}V_A - \frac{(I'_{MIN} - I_{MIN})V^2}{V_A}\right]$$

Developing this equation,

$$T = K_1 \left\{ - IV[\sin(\tau - \phi)\cos\rho + \cos(\tau - \phi)\sin\rho] - I_{MIN}V_A - \frac{(I_{MIN}' - I_{MIN})V^2}{V_A} \right\}$$

But

$$I = I_{MAX}\sin\frac{\theta}{2} \qquad V\cos\rho = V_A\cos\frac{\theta}{2}$$

$$V\sin\rho = (1 - 2n)V_A\sin\frac{\theta}{2}$$

and from equation 2

$$V^2 = V_A^2\left[\cos^2\frac{\theta}{2} + (1 - 2n)^2\sin^2\frac{\theta}{2}\right]$$

Substituting in the torque equation,

$$T = K_1V_A\left\{I_{MAX}\left[(2n - 1)\cos(\tau - \phi)\sin^2\frac{\theta}{2} - \sin(\tau - \phi) \times \sin\frac{\theta}{2}\cos\frac{\theta}{2}\right] - I_{MIN} - (I'_{MIN} - I_{MIN})\left[(1 - 2n)^2\sin^2\frac{\theta}{2} + \cos^2\frac{\theta}{2}\right]\right\} \quad (5)$$

Derivation of Equation 6

Referring to figure 15,

$$X = -\frac{V}{I}\sin\omega = -\frac{V}{I}\sin(\rho + 90 - \phi)$$

$$= -\frac{V}{I}\cos(\rho - \phi)$$

$$= -\frac{V}{I}[\cos\rho\cos\phi + \sin\rho\sin\phi]$$

But $V\cos\rho = V_A\cos\frac{\theta}{2}$ $\qquad$ $V\sin\rho = (1 - 2n)V_A\sin\frac{\theta}{2}$

Therefore,

$$X = \frac{V_A}{I}\left[(2n - 1)\sin\frac{\theta}{2}\sin\phi - \cos\frac{\theta}{2}\cos\phi\right]$$

But

$$I = \frac{2V_A}{Z'}\sin\frac{\theta}{2}$$

Therefore,

$$X = \frac{Z'}{2}\left[(2n - 1)\sin\phi - \cot\frac{\theta}{2}\cos\phi\right] \quad (6)$$

Derivation of Equation 7

Referring to figure 15,

$$Z = \frac{V}{I}$$

But

$$V = V_A\sqrt{(1 - 2n)^2\sin^2\frac{\theta}{2} + \cos^2\frac{\theta}{2}}$$

and

$$I = \frac{2V_A}{Z'}\sin\frac{\theta}{2}$$

Therefore

$$Z = \frac{Z'}{2}\sqrt{(1 - 2n)^2 + \cot^2\frac{\theta}{2}} \quad (7)$$

Symbols

V_A V_F = line-to-neutral root-mean-square secondary voltage behind transient reactance at source A and at source F
V_B, V_C, V_D, and V_E = line-to-neutral root-mean-square secondary voltage at substations B, C, D, and E
V = line-to-neutral root-mean-square secondary voltage at any location
I = root-mean-square secondary current at any location
I_{MIN} = minimum root-mean-square pick-up current of a directional relay
I_{MIN}' = minimum root-mean-square pick-up current of a directional relay with voltage restraint
I_{MAX} = maximum root-mean-square secondary current during an oscillation
$I_{p.u.}$ = root-mean-square pick-up current of a relay
θ = displacement angle
ϕ = natural system phase angle
ω = angle between V and I
τ = angle of maximum torque of a directional relay with or without voltage restraint
ρ = angle used in construction for derivation of equations
T = relay torque
n = per-unit impedance
Z' = total system secondary line-to-neutral impedance
Z = secondary line-to-neutral impedance indicated to an impedance relay
X = secondary line-to-neutral reactance indicated to a reactance relay
K_1, K_2, and K_3 = constants

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A Comprehensive Method of Determining the Performance of Distance Relays

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Introduction

DURING the past few years rapid progress has been made in the development of distance relay protective schemes, and there are now available a number of various types of distance measuring and directional elements which may be utilized in various combinations to afford the protection desired. In determining the performance of these elements under various fault conditions it would be of great benefit to be able to express the performance of each type of element under a given fault condition in terms of a simple quantity such as the effective line impedance between the relay and the point of fault. Unfortunately it will be found that the performance of certain elements, notably those connected to the unfaulted phases will be affected by changes in system setup and in system capacity. Lewis and Tippet have provided an excellent theoretical treatment of this problem[1] which Calabrese has supplemented by a study of the effect of wye-delta and delta-wye transformers interposed between the relay and the fault.[2]

Fundamentally, the performance of any distance element is a function of the current and voltage applied to the relay and of the vector angle between them. Unless this relationship becomes equal to a definite impedance which is present in the system network, the practice heretofore has been to determine the performance of the element for a given fault condition by the calculation of the current, voltage, and vector angle involved.

The calculation of these currents, voltages, and angles involves the use of certain fundamental impedances and current distribution factors which are characteristic of the system set-up, fault and relay location; but which are independent of the type of fault. By expressing the performance of the relay directly in terms of these fundamental quantities for any type of fault, the labor involved in the determination of the relay performance for any specific case will be reduced to a minimum.

The determination of these fundamental quantities may present considerable difficulty, and in the case of the complicated system networks commonly met with in practice, their accurate determination is practically impossible without the use of an a-c calculating table. An approximate determination is possible, however, by the use of a d-c calculating table, and the general expressions for relay performance will be presented in such a form that the approximate values thus obtained for the fundamental quantities may be used instead of the more accurate values. The accuracy of the results obtained will, of course, be dependent upon the accuracy of the fundamental assumption necessary in the use of the d-c calculating table; i.e., that all of the impedances appearing in the system networks have the same power factor angles.

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1. For all numbered references, see list at end of paper.

Summary

This paper presents a comprehensive method of determining the performance of distance relays along the lines indicated above which may be summarized as follows:

1. A general method by which the performance of any of the types of distance elements in common use may be determined from the effective impedance presented to the element.

2. A tabulation from which the effective impedance presented to any type of distance element under any condition of fault may be obtained in terms of the effective line impedance between the relay and the fault and 4 quantities which are characteristic of the system setup and location of the fault with reference to the relay. These quantities may be determined approximately by the use of a d-c calculating table setup.

3. A method for including the effect of fault resistance in the determination of the effective impedance presented to the relay.

4. Methods by which the performance of standard directional elements under fault conditions may be determined.

5. An extension of the general method to enable the expression of the operating time of *CZ* relays in terms of the effective impedance presented to the relay.

6. An extension of the general method to include the performance of distance relays connected for protection against single-phase-to-ground faults.

Types of Distance Relays Considered

While the method outlined in this paper is primarly intended to encompass all forms of distance relays operative on interphase faults, i.e., those relays which are connected to phase-to-phase potentials, it nevertheless is also applicable to the case of relays connected to phase-to-neutral-potentials with or without current compensation, which are intended to protect against single-phase-to-ground faults only Since this connection may be regarded as a special application, it will be treated subsequent to the general method.

With the exception of the *CZ* relay, the time of operation of which varies with the effective impedance presented to the relay, all of the distance relays in general use in the United States are either of the instantaneous

type or are composed of elements which are of that type. The method of solution will, therefore, be indicated on the basis of instantaneous elements with no further reference as to their time of operation. The *CZ* relay will be subsequently treated as a special case.

For purposes of treatment, distance elements may be classified both as to function and as to connections. Under the former classification the following types are evident:

(*a*) Impedance elements (types *CZ, HZ, IGX, IJX*)

(*b*) Reactance elements (type *HX*, ohm units of types *GAX, GCX*)

(*c*) Modified reactance elements (type *HY*)

(*d*) Directional elements with voltage restraint (starting units of types *GAX* and *GCX*, polyphase types *CHV*-3, *IDP, CBP*)

In regard to classification as to connections, the following distinctions may be drawn:

(*a*) One current and one voltage (types *CZ, HZ, IGX, IJX, HY, HX*, ohm units of type *GAX, GCX*, starting unit of type *GAX*)

1. Star-connected current transformers
2. Delta-connected current transformers

(*b*) One current and 2 voltages (starting unit of type *GCX*)

(*c*) Three currents and 3 voltages (type *CHV*-3, *IDP, CBP*)

In the above classification, the first group of elements is indicated as being operative from either star-or delta-connected current transformers. Actually the effect of delta-connected current transformers may be obtained by the delta connection of the main current transformer secondaries, the use of auxiliary secondary current transformers, or by the use of double coil elements. For simplicity, the problem will be treated as if the first method were employed. The use of any other method will not affect the theory and will merely change the value of the constant indicative of the relay setting.

Distance Relay Equations

The operation of any simple relay element involves the resultant torque produced in the element by the application of a current and/or a voltage. This torque may be made up of torques produced by the current alone, the voltage alone, and the interaction of the current and the voltage. In the case of a distance measuring element, the resultant torque at the balance point must equal zero and the following general equation may be written to express this fact

$$K_v V^2 - K_i I^2 - K_{iv} I V \cos(\phi_V - \phi_I - \psi) = 0 \qquad (1)$$

in which the first term is indicative of the torque produced by the voltage alone tending to open the contacts, the second term is indicative of the torque produced by the current alone tending to close the contacts, and the third term indicates the interaction torque in which the angle ψ is the vector angle between current and voltage at which this interaction torque is a maximum.

Equation 1 may be expressed in terms of Z the effective impedance presented to the relay by dividing by $K_v I^2$.

$$Z^2 - \frac{K_{iv}}{K_v} Z \cos(\phi_Z - \psi) = \frac{K_i}{K_v} \qquad (2)$$

Equation 2 may be transformed into the following form by the addition of $(K_{iv}/2K_v)^2$ to both sides.

$$Z^2 + \left(\frac{K_{iv}}{2K_v}\right)^2 - \frac{K_{iv}}{K_v} Z \cos(\phi_Z - \psi) = \left(\frac{\sqrt{K_{iv}^2 + 4K_iK_v}}{2K_v}\right)^2 \qquad (3)$$

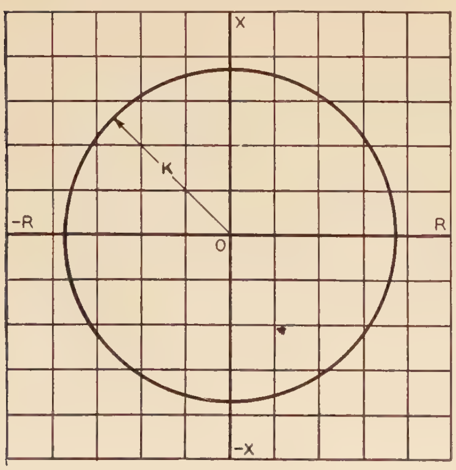
Equation 3 will be recognized as the equation of a circle expressed in terms of the polar co-ordinates Z and ϕ_Z. The radius of this circle is $(K_{iv}^2 + 4K_iK_v)/2K_v$ and its center is located at a distance $K_{iv}/2K_v$ from the origin at the angle ψ from the reference vector.

It is therefore apparent that the balance point of any distance element may be expressed graphically on an impedance diagram as a characteristic circle and in order to determine whether or not the element will operate under a given fault condition, it is merely necessary to determine the effective impedance presented to the relay under that fault condition and to locate it on the diagram. If it falls within the circle the relay will operate, and the relay will not operate if it falls outside of the circle.

Equation 2 is a quadratic and may be solved for Z giving the following expression

$$\left[\frac{K_{iv}}{2K_v}\cos(\phi_Z - \psi) \pm \frac{\sqrt{K_{iv}^2\cos^2(\phi_Z - \psi) + 4K_iK_v}}{2K_v}\right]\angle\phi_Z = Z\angle\phi_Z \qquad (4)$$

Figure 1. Characteristic figure for an impedance relay



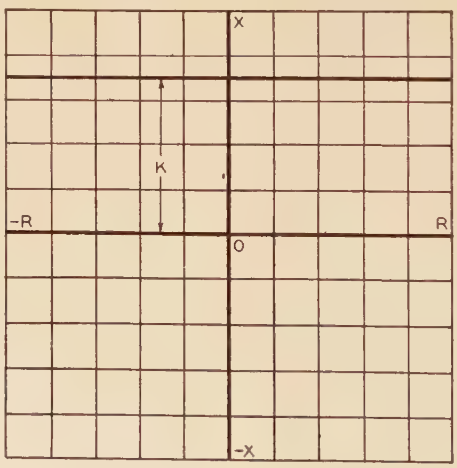
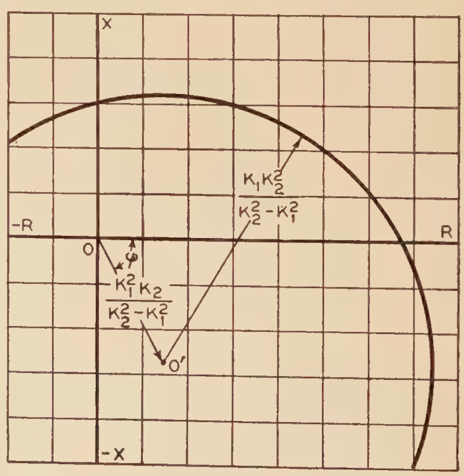


Figure 2. Characteristic figure for a reactance relay

Figure 3. Characteristic figure for a modified reactance relay



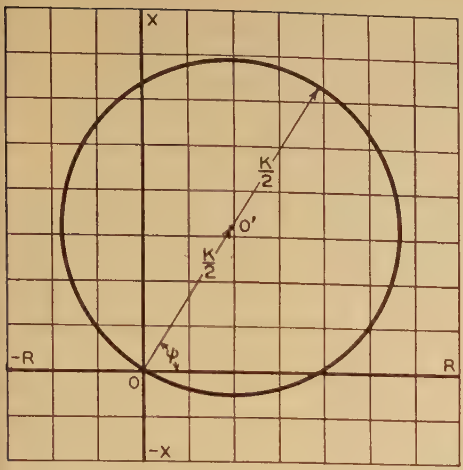


Figure 4. Characteristic figure for a directional relay with voltage restraint

Both sides of equation 4 have been multiplied by $\epsilon^{j\phi_z}$ (herein indicated as $\angle\phi_z$) in order to indicate that the effective impedance presented to the element is to be used as a vector quantity in determining its performance. As previously indicated the left-hand side of the equation when plotted for all possible values of ϕ_z will be a circle.

By the proper evaluation of the constants, equation 4 may be made to assume the following forms which are characteristic of the various types of distance elements previously classified. The derivation of these equations in the conventional manner is given in appendix *A*.

(*a*) Impedance Element

$$K_{iv} = 0; \qquad \sqrt{K_i/K_v} = K \tag{5}$$

$$K\angle\phi_z = Z\angle\phi_z = \frac{V}{I}\angle\phi_V - \phi_I \tag{6}$$

The characteristic circle for this element shown in figure 1 has a radius equal to K with its center at the origin.

(*b*) Reactance Element

$$K_v = 0; \qquad K_i/K_{iv} = K; \qquad \psi = -90° \tag{7}$$

$$\frac{K\angle\phi_z}{\sin\ \phi_z} = Z\angle\phi_z = \frac{V}{I}\angle(\phi_V - \phi_I) \tag{8}$$

The characteristic circle for the element shown in figure 2 has a radius equal to infinity with its center located at infinity. It is therefore a straight line and has a minimum distance of K from the origin.

(*c*) Modified Reactance Element

In this element all of the torque terms are utilized.

$$K_1 = 1; \qquad K_v = \frac{1}{K_1^2} - \frac{1}{K_2^2}; \qquad K_{iv} = \frac{2}{K_2} \tag{9}$$

$$\left[\frac{K_1^2K_2}{K_2^2 - K_1^2}\cos(\phi_z - \psi) + \sqrt{\left(\frac{K_1^2K_2}{K_2^2 - K_1^2}\right)^2\cos^2(\phi_z - \psi) + \left(\frac{K_1K_2^2}{K_2^2 - K_1^2}\right)^2 - \left(\frac{K_1^2K_2}{K_2^2 - K_1^2}\right)^2}\,\right]$$

$$\angle\phi_z = Z\angle\phi_z = \frac{V}{I}\angle(\phi_V - \phi_I) \tag{10}$$

The characteristic circle for this element shown in figure 3 has a radius of $K_1K_2^2/(K_2^2-K_1^2)$ with its center located $K_1^2K_2/(K_2^2-K_1^2)$ distant from the origin.

(*d*) Directional Element With Voltage Restraint

$$K_1 = 0; \qquad K_{iv}/K_v = K \tag{11}$$

1. *GAX Type*

$$K\cos(\phi_z - \psi)\angle\phi_z = \frac{1}{S}Z\angle\phi_z = \frac{1}{S}\frac{V}{I}\angle\phi_V - \phi_I \tag{12}$$

2. *GCX Type*

$$K\cos(\phi_z - \psi)\angle\phi_z = Z\angle\phi_z =$$

$$\frac{V}{I}\angle(\phi_V - \phi_I) \times \frac{2}{\sqrt{3}}\sin(\phi_V - \phi_{Vq})\angle(90° + \phi_{Vq} - \phi_V) \tag{13}$$

3. *Polyphase Type*

$$K\cos(\phi_z - \psi)\angle\phi_z = Z\angle\phi_z = \frac{3}{\dfrac{1}{Z_a\angle\phi_{za}} + \dfrac{1}{Z_b\angle\phi_{zb}} + \dfrac{1}{Z_c\angle\phi_{zc}}} \tag{14}$$

The characteristic circle for these elements shown in figure 4 has a radius equal to $K/2$ with its center located at the same distance from the origin.

In equation 12, S is a factor indicative of the variation in range of the unit with variation of the applied potential. This is discussed in appendix *A*.

In the equation 14, the quantities Z_a, Z_b, and Z_c are the effective impedances presented to the respective phase *GCX* type units as determined from equation 13.

In view of the above equations, it is evident that the performance of all of the above mentioned types of elements for a given fault can be completely expressed by 4 characteristic graphical figures (3 circles and a straight line) and the solution of the requisite equivalent expressions for $Z\angle\phi_z$. Actually in the case of relays connected for protection against interphase faults, since 3 individual phase relays are involved in all but the last type and since the first 3 types of elements may or may not employ delta-connected current transformers (or their equivalent) 10 such solutions must be made. These solutions may be summarized in tabular form by the equations given below.

Since the expression $Z\angle\phi_z$ and its equivalents are vectors we will be dealing hereafter entirely with vectors, which will be indicated by bold-face type.

(*a*) One Current and One Voltage

(Impedance, reactance, modified reactance, *GAX* starting unit)

1. *Star-Connected Current Transformers*

$$\mathbf{Z}_a = \frac{\mathbf{V}_{ba}}{\mathbf{I}_a} \tag{15}$$

$$\mathbf{Z}_b = \frac{\mathbf{V}_{ab}}{\mathbf{I}_b} \tag{16}$$

$$\mathbf{Z}_c = \frac{\mathbf{V}_{ac}}{\mathbf{I}_c} \tag{17}$$

2. *Delta-Connected Current Transformers*

$$\mathbf{Z}_a' = \frac{\mathbf{V}_{ba}}{\mathbf{I}_a'} \tag{18}$$

$$\mathbf{Z}_b' = \frac{\mathbf{V}_{cb}}{\mathbf{I}_b'} \tag{19}$$

$$\mathbf{Z}_c' = \frac{\mathbf{V}_{ac}}{\mathbf{I}_c'} \tag{20}$$

Table I. Relay Voltages and Currents in Terms of Fundamental Quantities for Various Fault Conditions

		Three-Phase Fault	No Phase Shift in Voltage Between Relay and Fault		
			Phase-Phase Fault	Phase-Ground Fault	Two-Phase-Ground Fault
Voltages	V_{ba}	$\sqrt{3}\frac{c_1}{Z_1} z\, E\angle 30°$ $= \frac{\sqrt{3}}{2}\frac{c_1 z}{Z_1} A\, E\angle 90°$	$1.5\left(1 + \frac{c_1 z}{\sqrt{3}Z_1}\angle 90°\right)E$ $= \frac{\sqrt{3}}{2}\frac{c_1 z}{Z_1} A\, E\angle 90°$	$\frac{\sqrt{3}}{2}\left(\sqrt{3}\frac{2c_1 z + Z_0}{2Z_1 + Z_0} + 1\angle 90°\right)E$ $= \frac{\sqrt{3}}{2} AE\angle 90°$	$1.5\left(\frac{c_1 z + 2Z_0}{Z_1 + 2Z_0} + \frac{c_1 z}{\sqrt{3}\, Z_1}\angle 90°\right)E$ $= \frac{\sqrt{3}}{2}\frac{c_1 z}{Z_1} AE\angle 90°$
	V_{cb}	$\sqrt{3}\frac{c_1}{Z_1} z\, E\angle -90°$	$\sqrt{3}\frac{c_1 z}{Z_1} E\angle -90°$	$\sqrt{3}\, E\ \angle -90°$	$\sqrt{3}\frac{c_1 z}{Z_1} E\angle -90°$
	V_{ac}	$\sqrt{3}\frac{c_1}{Z_1} z\, E\angle 150°$ $= \frac{\sqrt{3}}{2}\frac{c_1 z}{Z_1} BE\angle 90°$	$1.5\left(-1 + \frac{c_1 z}{\sqrt{3}Z_1}\angle 90°\right)E$ $= \frac{\sqrt{3}}{2}\frac{c_1 z}{Z_1} BE\angle 90°$	$\frac{\sqrt{3}}{2}\left(-\sqrt{3}\frac{2c_1 z + Z_0}{2Z_1 + Z_0} + 1\angle 90°\right)E$ $= \frac{\sqrt{3}}{2} BE\angle 90°$	$1.5\left(-\frac{c_1 z + 2Z_0}{Z_1 + 2Z_0} + \frac{c_1 z}{\sqrt{3}\, Z_1}\angle 90°\right)E$ $= \frac{\sqrt{3}}{2}\frac{c_1 z}{Z_1} BE\angle 90°$
Currents, Star-Connected Current Transformers	I_a	$\frac{c_1}{Z_1} E$	0	$\frac{2c_1 + c_0}{2Z_1 + Z_0} E$	$\frac{c_1 - c_0}{Z_1 + 2Z_0} E$
	I_b	$\frac{c_1}{Z_1} E\angle -120°$	$\frac{\sqrt{3}c_1}{2Z_1} E\angle -90°$	$-\frac{c_1 - c_0}{2Z_1 + Z_0} E$	$\frac{1}{2}\left(-\frac{c_1 + 2c_0}{Z_1 + 2Z_0} - \sqrt{3}\frac{c_1}{Z_1}\angle 90°\right)E$ $= \frac{\sqrt{3}}{2}\frac{c_1}{Z_1} CE\angle -90°$
	I_c	$\frac{c_1}{Z_1} E\angle 120°$	$\frac{\sqrt{3}\, c_1}{2Z_1} E\angle 90°$	$-\frac{c_1 - c_0}{2Z_1 + Z_0} E$	$\frac{1}{2}\left(-\frac{c_1 + 2c_0}{Z_1 + 2\, Z_0} + \sqrt{3}\frac{c_1}{Z_1}\angle 90°\right)E$ $= \frac{\sqrt{3}}{2}\frac{c_1}{Z_1} DE\angle 90°$
Currents, Delta-Connected Current Transformers	I_a'	$\sqrt{3}\frac{c_1}{Z_1} E\angle 30°$	$\frac{\sqrt{3}c_1}{2Z_1} E\angle 90°$	$\frac{3\, c_1}{2Z_1 + Z_0} E$	$1.5c_1\left(\frac{1}{Z_1 + 2Z_0} + \frac{1}{\sqrt{3}\, Z_1}\angle 90°\right)E$ $= \frac{\sqrt{3}}{2}\frac{c_1}{Z_1} C'E\angle 90°$
	I_b'	$\sqrt{3}\frac{c_1}{Z_1} E\angle -90°$	$\frac{\sqrt{3}c_1}{Z_1} E\angle -90°$	0	$\sqrt{3}\frac{c_1}{Z_1} E\angle -90°$
	I_c'	$\sqrt{3}\frac{c_1}{Z_1} E\angle 150°$	$\frac{\sqrt{3}c_1}{2Z_1} E\angle 90°$	$-\frac{3\, c_1}{2\, Z_1 + Z_0} E$	$1.5c_1\left(-\frac{1}{Z_1 + 2Z_0} + \frac{1}{\sqrt{3}\, Z_1}\angle 90°\right)E$ $= \frac{\sqrt{3}}{2}\frac{c_1}{Z_1} D'E\angle 90°$

(*b*) One Current and 2 Voltages

Star-connected current transformers (*GCX* starting unit)

$$Z_a'' = Z_a \times \frac{2}{\sqrt{3}} \sin(\phi_{Vba} - \phi_{Vcb}) \angle (90° + \phi_{Vcb} - \phi_{Vba}) \qquad (21)$$

$$Z_b'' = Z_b \times \frac{2}{\sqrt{3}} \sin(\phi_{Vcb} - \phi_{Vac}) \angle (90° + \phi_{Vac} - \phi_{Vcb}) \qquad (22)$$

$$Z_c'' = Z_c \times \frac{2}{\sqrt{3}} \sin(\phi_{Vac} - \phi_{Vba}) \angle (90° + \phi_{Vba} - \phi_{Vac}) \qquad (23)$$

(*c*) Three Currents and 3 Voltages

Star-connected current transformers (polyphase directional with voltage restraint)

$$Z_p = \frac{3}{\frac{1}{Z_a''} + \frac{1}{Z_b''} + \frac{1}{Z_c''}} \qquad (24)$$

Solution of Z

The solution of Z from equations 15–24 will be effected by the application of the method of symmetrical components to the determination of the various currents and voltages involved in these equations. It will be evident that these currents and voltages may be completely expressed in terms of the following quantities, all of which are to be considered as vectors.

E = the normal primary phase to neutral voltage at the relay

Z_1, Z_2, Z_0 = the equivalent impedances of the positive-, negative-, and zero-phase sequence networks, respectively, expressed at the voltage E

c_1, c_2, c_0 = the respective ratios of the positive-, negative-, and zero-phase-sequence currents at the relay to the corresponding total phase sequence currents at the point of fault

z = the *effective* (positive- or negative-phase sequence) impedance between the relay and the point of fault

Table I (Continued). Relay Voltages and Currents in Terms of Fundamental Quantities for Various Fault Conditions

		Thirty-Degree Phase Shift in Voltage Between Relay and Fault		
		Phase-Phase Fault	Phase-Ground Fault	Two-Phase-Ground Fault
Voltages		$\frac{\sqrt{3}}{2}\left(\sqrt{3}\frac{c_1 z}{Z_1}+1\angle 90°\right)E$	$1.5\left(1+\frac{1}{\sqrt{3}}\frac{2c_1 z+Z_0}{2Z_1+Z_0}\angle 90°\right)E$	$\frac{\sqrt{3}}{2}\left(\sqrt{3}\frac{c_1 z}{Z_1}+\frac{c_1 z+2Z_0}{Z_1+2Z_0}\angle 90°\right)E$
		$=\frac{\sqrt{3}}{2}AE\angle 90°$	$=\frac{\sqrt{3}}{2}\frac{2c_1 z+Z_0}{2Z_1+Z_0}AE\angle 90°$	$=\frac{\sqrt{3}}{2}\frac{c_1 z+2Z_0}{Z_1+2Z_0}AE\angle 90°$
		$\sqrt{3}E\angle -90°$	$\sqrt{3}\frac{2c_1 z+Z_0}{2Z_1+Z_0}E\angle -90°$	$\sqrt{3}\frac{c_1 z+2Z_0}{Z_1+2Z_0}E\angle -90°$
		$\frac{\sqrt{3}}{2}\left(-\sqrt{3}\frac{c_1 z}{Z_1}+1\angle 90°\right)E$	$1.5\left(-1+\frac{1}{\sqrt{3}}\frac{2c_1 z+Z_0}{2Z_1+Z_0}\angle 90°\right)E$	$\frac{\sqrt{3}}{2}\left(-\sqrt{3}\frac{c_1 z}{Z_1}+\frac{c_1 z+2Z_0}{Z_1+2Z_0}\angle 90°\right)E$
		$=\frac{\sqrt{3}}{2}BE\angle 90°$	$=\frac{\sqrt{3}}{2}\frac{2c_1 z+Z_0}{2Z_1+Z_0}BE\angle 90°$	$=\frac{\sqrt{3}}{2}\frac{c_1 z+2Z_0}{Z_1+2Z_0}BE\angle 90°$
Currents	Star-Connected Current Transformers	$\frac{c_1}{Z_1}E$	0	$\frac{c_1}{Z_1}E$
		$-\frac{c_1}{2Z_1}E$	$\frac{\sqrt{3}c_1}{2Z_1+Z_0}E\angle -90°$	$\frac{c_1}{2}\left(-\frac{1}{Z_1}-\frac{\sqrt{3}}{Z_1+2Z_0}\angle 90°\right)E$ $=\frac{\sqrt{3}}{2}\frac{c_1}{Z_1+2Z_0}CE\angle -90°$
		$-\frac{c_1}{2Z_1}E$	$\frac{\sqrt{3}c_1}{2Z_1+Z_0}E\angle 90°$	$\frac{c_1}{2}\left(-\frac{1}{Z_1}+\frac{\sqrt{3}}{Z_1+2Z_0}\angle 90°\right)E$ $=\frac{\sqrt{3}}{2}\frac{c_1}{Z_1+2Z_0}DE\angle 90°$
	Delta-Connected Current Transformers	$1.5\frac{c_1}{Z_1}E$	$\frac{\sqrt{3}c_1}{2Z_1+Z_0}E\angle 90°$	$\frac{\sqrt{3}}{2}c_1\left(\frac{\sqrt{3}}{Z_1}+\frac{1}{Z_1+2Z_0}\angle 90°\right)E$ $=\frac{\sqrt{3}}{2}\frac{c_1}{Z_1+2Z_0}C'E\angle 90°$
		0	$\frac{2\sqrt{3}c_1}{2Z_1+Z_0}E\angle -90°$	$\frac{\sqrt{3}c_1}{Z_1+2Z_0}E\angle -90°$
		$-1.5\frac{c_1}{Z_1}E$	$\frac{\sqrt{3}c_1}{2Z_1+Z_0}E\angle 90°$	$\frac{\sqrt{3}}{2}c_1\left(-\frac{\sqrt{3}}{Z_1}+\frac{1}{Z_1+2Z_0}\angle 90°\right)E$ $=\frac{\sqrt{3}}{2}\frac{c_1}{Z_1+2Z_0}D'E\angle 90°$

It is important to notice that z is the *effective* impedance between the relay and the point of fault and take into account not only the impedances of the lines and equipment in this path, but the relative current distribution as well. For instance, if the path comprises the impedances z, z', and z'', etc., with the corresponding current distribution factors $\mathbf{c}$, $\mathbf{c}'$, and $\mathbf{c}''$, then

$$z=\frac{cz+c'z'+c''z''\ldots}{c} \tag{25}$$

With relay elements not employing phase-to-neutral voltages the corresponding effective zero-phase-sequence impedance z_0 will not be needed since the phase-to-phase voltages are not dependent upon the voltage distribution through the zero-phase-sequence network.

In order to simplify the expressions to follow, the assumption has been made that the positive- and negative-phase-sequence networks are identical. This assumption is felt to be justifiable in work of this kind and considerably reduces the amount of calculation necessary to obtain the desired results. On this basis all currents and voltages may be expressed in terms of the fundamental quantities E, Z_1, Z_0, c_1, c_0, and z.

In considering the effect of the type of fault, 7 distinct types of faults must be recognized, since in addition to the symmetrical case of a 3-phase fault and the 3 unsymmetrical cases of phase-to-phase, phase-to-ground, and 2-phase-ground faults, these unsymmetrical faults occurring beyond a transformer bank which produces a phase shift in voltage constitute 3 more different cases.

If a wye-delta or delta-wye transformer bank is interposed between the relay and the fault, the positive-phase-sequence currents and voltages will be displaced 30 degrees in one direction (depending upon the bank connections)

and the negative-phase-sequence currents and voltages will be displaced 30 degrees in the other direction when passing through the bank. The effect of this upon the vector diagrams at the relay is such that they will be similar for a given type of fault irrespective of the direction of phase shift and may be made identical by choosing the phases to be involved in the fault with reference to the direction of the phase shift.

Three-phase faults produce no negative-phase-sequence components so that the presence of a bank between the point and the fault has no effect upon the vector diagram. Similarly delta-delta or wye-delta-wye banks produce no net phase shift and do not affect the vector diagram.

To summarize, the 7 distinct cases of faults must be recognized which are as follows:

1. Three-phase fault under any condition.
2. *B* phase — *C* phase fault with no voltage phase shift between the relay and the point of fault. This includes faults beyond a delta-delta or wye-delta-wye transformer bank.
3. *A* phase — ground fault under the conditions outlined in 2.
4. *B* phase — *C* phase — ground fault under the conditions outlined in 2.

5*a*. *A* phase — *B* phase — fault beyond a transformer bank connected so that the voltage on the fault side lags the voltage on the relay side by 30 degrees.

5*b*. *C* phase — *A* phase fault beyond a transformer bank connected so that the voltage on the fault side leads the voltage on the relay side by 30 degrees.

6*a*. *C* phase — ground fault under the conditions outlined in 5*a*.

6*b*. *B* phase — ground fault under the conditions outlined in 5*b*.

7*a*. *A* phase — *B* phase — ground fault under the conditions outlined in 5*a*.

7*b*. *C* phase — *A* phase — ground fault under the conditions outlined in 5*b*.

The values of the phase currents and voltages at the relay for each of these 7 cases in terms of the fundamental quantities are given in table I. Currents applicable to relays fed from delta-connected current transformers are indicated by a prime mark (′). The derivation of these expressions is given in appendix *B*.

The expressions for currents and voltages given in table I when substituted in equations 15–24 give the solutions of Z sought for each of the 7 cases of fault. These expressions are given in table II. In order to simplify the expressions thus obtained factors have been introduced in certain cases as indicated. These factors are, of course, vectors, and in the case of the factors applied to the simplification of the voltage expressions, their vector angles are indicative of certain of the angles of the voltage triangle. This fact permits the formulation of the expressions for Z'' in terms of the vector angles of the factors.

In utilizing the expressions given in tables I and II it is very important to realize that the quantities $\mathbf{c}_1$ and $\mathbf{c}_0$ which are vectors should be formulated on the basis of the direction of phase sequence current flow in the line under consideration with respect to the fault and not with respect to the direction of connection of the relay for which the effective impedance presented to it is desired. If the fault lies behind the relay the vector expression obtained for the impedance presented to the relay should be rotated 180 degrees.

Effect of Fault Resistance Upon Z

In dealing with the problem of fault resistance, it should be realized that the fundamental quantity to be considered in the usual case of an arc fault is the voltage drop across the arc. This is essentially dependent upon the length of the arc and independent of the fault current. Since we have chosen to express the performance of the relay in terms of a quantity having the dimensions of impedance, it is desirable to express the effect of the fault arc in terms of a resistance, realizing that this resistance, unlike the fundamental quantities dealt with heretofore, is a function of the actual fault. Futhermore, this fault resistance will affect the value of all of these fundamental quantities except E.

In formulating the effective fault resistance, the quantity $\mathbf{R}_f$ is to be treated as a phase sequence resistance at the point of fault which is in series with Z_1, Z_2, and Z_0 in the respective phase sequence networks. The values of $\mathbf{R}_f$ introduced into each network are all equal for any given type of fault, but are different for different types of faults. In order to determine the actual value of $\mathbf{R}_f$ for the various types of faults, a 3-phase fault will be assumed to consist of 3 simultaneous single-phase-to-ground arcs of equal length and a 2-phase-to-ground fault to consist of 2 simultaneous phase-to-ground faults of equal length. The magnitude of $\mathbf{R}_f$ will then be equal to $\mathbf{V}_A$, the voltage drop across the arc divided by the total faulted phase current for 3-phase, phase-to-ground, and 2-phase-to-ground faults, and equal to half the arc voltage divided by the faulted phase current for a phase-to-phase fault. If we assume that the magnitude of the total faulted phase current is unaffected by the presence of $\mathbf{R}_f$ the following relationships are evident.

(*a*) *Three Simultaneous Phase-to-Ground Faults*

$$\mathbf{R}_f = \frac{\mathbf{V}_A}{\mathbf{E}}\,\mathbf{Z}_1 \tag{26}$$

(*b*) *Phase-to-Phase Fault* (*not involving ground*)

$$\mathbf{R}_f = \frac{\mathbf{V}_A}{\mathbf{E}}\,\frac{\mathbf{Z}_1}{\sqrt{3}} \tag{27}$$

(*c*) *Single Phase-to-Ground Fault*

$$\mathbf{R}_f = \frac{\mathbf{V}_A}{\mathbf{E}}\,\frac{2\mathbf{Z}_1 + \mathbf{Z}_0}{3} \tag{28}$$

(*d*) *Two Simultaneous Phase-to-Ground Faults*

$$\mathbf{R}_f = \frac{\mathbf{V}_A}{\mathbf{E}}\,\frac{2\mathbf{Z}_1}{\sqrt{3}\mathbf{C}'} \tag{29}$$

The value of $\mathbf{C}'$ to be used in equation 29 is that for the case of a 2-phase-to-ground fault without phase shift in voltage between the relay and the fault. Equations 26–29 yield the magnitude of $\mathbf{R}_f$, and the vector angle which results from their solution has no significance. $\mathbf{R}_f$ thus determined should be used as a resistance vector and

Table II. Effective Impedances in Terms of Fundamental Quantities Presented to Distance Relay Elements for Various Fault Conditions

		Three-Phase Fault	No Phase Shift in Voltage Between Relay and Fault: Phase-Phase Fault	Phase-Ground Fault	Two-Phase-Ground Fault	Thirty-Degree Phase Shift in Voltage Between Relay and Fault: Phase-Phase Fault	Phase-Ground Fault	Two-Phase-Ground Fault
Factors	A	$2\angle -60°$	$1-\dfrac{\sqrt{3}Z_1}{c_1z}\angle 90°$	$1-\sqrt{3}\dfrac{2c_1z+Z_0}{2Z_1+Z_0}\angle 90°$	$1-\dfrac{\sqrt{3}\,Z_1}{c_1z}\left(\dfrac{c_1z+2Z_0}{Z_1+2Z_0}\right)\angle 90°$	$1-\sqrt{3}\dfrac{c_1z}{Z_1}\angle 90°$	$1-\sqrt{3}\dfrac{2Z_1+Z_0}{2c_1+Z_0}\angle 90°$	$1-\sqrt{3}\dfrac{c_1z}{Z_1}\left(\dfrac{Z_1+2Z_0}{c_1z+2Z_0}\right)\angle 90°$
	B	$2\angle 60°$	$1+\dfrac{\sqrt{3}Z_1}{c_1z}\angle 90°$	$1+\sqrt{3}\dfrac{2c_1z+Z_0}{2Z_1+Z_0}\angle 90°$	$1+\dfrac{\sqrt{3}\,Z_1}{c_1z}\left(\dfrac{c_1z+2Z_0}{Z_1+2Z_0}\right)\angle 90°$	$1+\sqrt{3}\dfrac{c_1z}{Z_1}\angle 90°$	$1+\sqrt{3}\dfrac{2Z_1+Z_0}{2c_1+Z_0}\angle 90°$	$1+\sqrt{3}\dfrac{c_1z}{Z_1}\left(\dfrac{Z_1+2Z_0}{c_1z+2Z_0}\right)\angle 90°$
	C				$1-\dfrac{Z_1}{\sqrt{3}\,c_1}\left(\dfrac{c_1+2c_0}{Z_1+2Z_0}\right)\angle 90°$			$1-\dfrac{Z_1+2Z_0}{\sqrt{3}\,Z_1}\angle 90°$
	D				$1+\dfrac{Z_1}{\sqrt{3}\,c_1}\left(\dfrac{c_1+2c_0}{Z_1+2Z_0}\right)\angle 90°$			$1+\dfrac{Z_1+2Z_0}{\sqrt{3}\,Z_1}\angle 90°$
	C'				$1-\dfrac{\sqrt{3}\,Z_1}{Z_1+2Z_0}\angle 90°$			$1-\sqrt{3}\dfrac{Z_1+2Z_0}{Z_1}\angle 90°$
	D'				$1+\dfrac{\sqrt{3}\,Z_1}{Z_1+2Z_0}\angle 90°$			$1+\sqrt{3}\dfrac{Z_1+2Z_0}{Z_1}\angle 90°$
Elements With One Current and One Voltage — Star-Connected Cts.	$Z_a=\dfrac{V_{ba}}{I_a}$	$\sqrt{3}\,z\angle 30°$	∞	$\dfrac{\sqrt{3}}{2}A\dfrac{2Z_1+Z_0}{2c_1+c_0}\angle 90°$	$\dfrac{\sqrt{3}}{2}A\dfrac{c_1z}{Z_1}\left(\dfrac{Z_1+2Z_0}{c_1-c_0}\right)\angle 90°$	$\dfrac{\sqrt{3}}{2}A\dfrac{Z_1}{c_1}\angle 90°$	∞	$\dfrac{\sqrt{3}}{2}A\dfrac{Z_1}{c_1}\left(\dfrac{c_1z+2Z_0}{Z_1+2Z_0}\right)\angle 90°$
	$Z_b=\dfrac{V_{cb}}{I_b}$	$\sqrt{3}\,z\angle 30°$	$2z$	$\sqrt{3}\dfrac{2Z_1+Z_2}{c_1-c_0}\angle 90°$	$\dfrac{2}{c}z$	$2\sqrt{3}\dfrac{Z_1}{c_1}\angle 90°$	$\dfrac{2c_1z+Z_0}{c_1}$	$\dfrac{2}{c}\,\dfrac{c_1z+Z_0}{c_1}$
	$Z_c=\dfrac{V_{ac}}{I_c}$	$\sqrt{3}\,z\angle 30°$	Bz	$\dfrac{\sqrt{3}}{2}B\dfrac{2Z_1+Z_0}{c_1-c_0}\angle -90°$	$\dfrac{B}{D}z$	$\sqrt{3}\,B\dfrac{Z_1}{c_1}\angle -90°$	$\dfrac{B}{2}\,\dfrac{2c_1z+Z_0}{c_1}$	$\dfrac{B}{D}\,\dfrac{c_1z+2Z_0}{c_1}$
Elements With One Current and One Voltage — Delta-Connected Cts.	$Z_a'=\dfrac{V_{ba}}{I_a'}$	z	Az	$\dfrac{A}{2\sqrt{3}}\,\dfrac{2Z_1+Z_0}{c_1}\angle 90°$	$\dfrac{A}{c'}z$	$\dfrac{A}{\sqrt{3}}\,\dfrac{Z_1}{c_1}\angle 90°$	$\dfrac{A}{2}\,\dfrac{2c_1z+Z_0}{c_1}$	$\dfrac{A}{c'}\,\dfrac{c_1z+2Z_0}{c_1}$
	$Z_b'=\dfrac{V_{cb}}{I_b'}$	z	z	∞	z	∞	$\dfrac{1}{2}\,\dfrac{2c_1z+Z_0}{c_1}$	$\dfrac{c_1z+2Z_0}{c_1}$
	$Z_c'=\dfrac{V_{ac}}{I_c'}$	z	Bz	$\dfrac{B}{2\sqrt{3}}\,\dfrac{2Z_1+Z_0}{c_1}\angle -90°$	$\dfrac{B}{D'}z$	$\dfrac{B}{\sqrt{3}}\,\dfrac{Z_1}{c_1}\angle -90°$	$\dfrac{B}{2}\,\dfrac{2c_1z+Z_0}{c_1}$	$\dfrac{B}{D'}\,\dfrac{c_1z+2Z_0}{c_1}$

Elements With One Current and 2 Voltages—Star-Connected Current Transformers

$Z_a'' = Z_a \times \dfrac{2}{\sqrt{3}} \sin(-\phi_A)\angle(-90° - \phi_A)$ $\qquad$ $Z_b'' = Z_b \times \dfrac{2}{\sqrt{3}} \sin \phi_B \angle(\phi_B - 90°)$ $\qquad$ $Z_c'' = Z_c \times \dfrac{2}{\sqrt{3}} \sin(\phi_B - \phi_A)\angle(90° + \phi_A - \phi_B)$

Element With 3 Currents and 3 Voltages—Star-Connected Current Transformers—90-Degree Potential Connection

$$Z_p = \frac{3}{\dfrac{1}{Z_a''} + \dfrac{1}{Z_b''} + \dfrac{1}{Z_c''}}$$

should be applied if necessary in the correction of the fundamental quantities.

R_f must be included in the determination of z and equation 25 may be rewritten as follows

$$z = \frac{cz + c'z' + c''z'' \ldots + R_f}{c} \tag{30}$$

Use of a D-C Calculating Table

If a d-c calculating table is employed to obtain the fundamental quantities mentioned above, it is of course impossible to treat them as vectors with different vector angles. If the usual practice of setting up the calculating table on the basis of the reactive components of impedance is followed, then the vector angles of c_1 and $\pm c_0$ will be zero and the vector angles of Z_1 and Z_0 will be 90 degrees. It is still possible to synthesize z with a fair degree of accuracy from equations 25 or 30 and a knowledge of the impedances of the branches in the path between the relay and the fault. The effect of arc resistance is included only in the computation of z.

The results obtained by this procedure will usually be sufficiently accurate for most purposes, but it must be realized that in the case of a fault on the end of a line having a relatively large resistive component and fed by a system which is highly reactive, the impedances thus determined for the unfaulted phase relays may be subject to an appreciable error. The limitations introduced are, of course, due to the use of the d-c calculating table and not to the expressions given in tables I and II which are rigorous except for the assumption that the positive- and negative-phase-sequence networks are identical.

Under the assumptions necessitated by the use of the d-c calculating table the solution for Z_p the effective impedance presented to the polyphase unit is greatly simplified and the following expressions may be used in place of equation 24.

Three-Phase Fault

$$Z_p = \sqrt{3}z \tag{31}$$

Phase-to-Phase Fault

$$Z_p = 2\sqrt{3}z \tag{32}$$

Phase-to-Ground Fault

$$Z_p = \sqrt{3}\left(\frac{2c_1z + Z_0}{c_1}\right) \tag{33}$$

Two-Phase-to-Ground Fault

$$Z_p = \sqrt{3}\left(\frac{c_1z + 2Z_0}{c_1z + Z_0}\right)z \tag{34}$$

Equations 31–34 apply whether or not there is a phase shift in voltage between the relay and the fault.

Performance of Directional Elements Without Voltage Restraint

Distance relays are almost invariably of the directional type. The type *GAX* and *GCX* reactance relays are given directional characteristics by means of the starting units discussed above. The *CZ*, *HZ*, *HY*, and *IGX* types are made directional by the use of a conventional directional element suitably connected to the circuit. In interpreting the performance of such relays, it is necessary to know whether or not the various phase distance elements will be released by their associated directional elements.

In the case of *CZ*, *HZ*, and *HY* relays a true wattmetric type of element is used with a 30 degree connection. That is the *A*-phase relay is connected to the current I_a and the voltage V_{ac} reversed and so on. It will be evident, therefore, that the vector angle between the voltage and current applied to the directional element is equal to the vector angle of the impedance presented to the distance element minus the corresponding internal angle of the voltage triangle. The directional element will operate if the angle thus obtained lies between $\pm$ 90 degrees. Solutions of the following expressions are therefore required.

$$A \text{ phase:}\quad \phi_{Za} - 180° + \phi_{Vac} - \phi_{Vba} \tag{35}$$

$$B \text{ phase:}\quad \phi_{Zb} - 180° + \phi_{Vba} - \phi_{Vcb} \tag{36}$$

$$C \text{ phase:}\quad \phi_{Zc} - 180° + \phi_{Vcb} - \phi_{Vac} \tag{37}$$

In view of the angular relationships developed in appendix *B* expressions 35–37 become:

$$A \text{ phase:}\quad \phi_{Za} - 180° + \phi_B - \phi_A \tag{38}$$

$$B \text{ phase:}\quad \phi_{Zb} + \phi_A \tag{39}$$

$$C \text{ phase:}\quad \phi_{Zc} - \phi_B \tag{40}$$

If delta connected current transformers are employed for the directional elements, ϕ_z' should be substituted for ϕ_z in expressions 35–40.

In the case of the *IGX* relay, a 90 degree connection is used for the directional element. (*A*-phase relay is connected to the current I_a and the voltage V_{bc} and so on) and the angle of maximum torque of the element is variable within certain limits. The angular range of operation of this element is therefore similar to that ot the type *GCX* starting unit and therefore the element will operate if the vector angle of Z'' lies within $\pm$90 degrees of ψ where ψ is now to be interpreted as the angle of maximum torque of the directional element.

If delta-connected current transformers are used with the directional element of *IGX* relay, Z'' should be formulated from Z' rather than from Z.

It should be noted, however, that by the use of auxiliary current transformers it is possible to obtain the effect of delta-connected current transformers on the distance elements and at the same time maintain the more desirable effect of star-connected current transformers on any type of directional element.

Determination of CZ Relay Operating Times

Unlike the instantaneous distance elements previously discussed which either do or do not operate according to the value of Z presented to the element, the *CZ* relay operates in a time which is more or less a direct function of the magnitude of Z. The characteristic time curves for this relay have usually been expressed as a set of current-

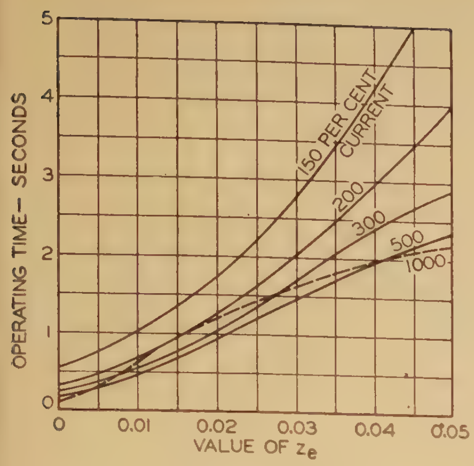


Figure 5. Time-impedance characteristics of CZ relays

time curves, each curve being for a constant voltage maintained at the relay terminals. This method is unsatisfactory because it fails to bring out the constant time-impedance relationship which is the inherent principle of operation for which the relay is designed. This may be done by plotting a set of time-impedance curves, each curve being for a constant current applied to the relay. Figure 5 shows such a set of curves plotted in terms of an impedance parameter z_e for various values of current expressed in per cent of current tap setting. The parameter z_e is so constituted that it bears the following relationship to Z

$$z_e = \frac{T_c R_c}{T_v R_v} Z \tag{41}$$

in which:

T_c = the current tap setting of the relay
T_v = the voltage tap setting of the relay
R_c = the current transformer ratio
R_v = the potential transformer ratio

The derivation of equation 41 and the curves of figure 5 is given in appendix A. Having determined the value of Z in exactly the same manner as for the case of an instantaneous impedance element, equation 41 and the use of the curves of figure 5 permit the determination of the relay operating time. Unfortunately, as is evident from the curves of figure 5, this operating time is a function of the current in the relay. It will, therefore, be necessary to solve the proper expression for current given in table I and express this value as a percentage of $T_c R_c$ in order to determine which curve of figure 5 applies.

Distance Relays for Ground Faults

The application of distance relays for protection against single-phase-to-ground faults has been discussed by Lewis and Tippett,[1] A. R. van C. Warrington,[3] and Goldsborough and Smith.[4] From these discussions it appears that a reactance type of element is indicated, connected to the the phase-to-neutral potential of the phase at fault and supplied with the faulted phase current compensated by a certain amount of residual current dependent upon the ratio of the effective zero-phase-sequence impedance between the relay and the fault to the effective positive-phase-sequence impedance between the same points. Further it is generally agreed that the relay so connected must be rendered inoperative in case more than one phase is involved in the fault. On this basis the effective impedance presented to the relay in the case of a single-phase-to-ground fault will be:

$$Z_{a0} = \frac{V_{oa}}{I_a + \frac{M-1}{3} I_n} \tag{42}$$

This becomes:

$$Z_{a0} = \frac{2c_1 z + c_0 z_0}{2c_1 + Mc_0} = z \tag{43}$$

If

$$M = \frac{z_0}{z} \tag{44}$$

It should be remembered that z_0 in the above expression is an *effective* value and takes into account not only the zero-phase-sequence impedances of the lines and equipment in the path between the relay and the fault, but also the relative current distribution and, most important, the effect of mutual induction of zero-phase-sequence currents flowing in parallel circuits.

Appendix A—Derivation of Distance Element Equations

In an instantaneous distance element 2 torques, an operating torque and a restraining torque are placed in opposition. The relay will be assumed to operate under conditions such that the operating torque is equal to or greater than the restraining torque and to be balanced when these torques are equal. These torques are functions of the fluxes produced in the relay coils and the angles between them. Since these fluxes are proportional to and have angles equal to the currents in the relay coils, the following balance equations will be derived from the currents themselves without further reference to the fluxes produced by them. The following nomenclature will be used.

I = current in the current coil
V, V_q = voltages applied to the potential coils
z_p, z_p' = impedances of the potential coil circuits
k, k' = balance constants
K, K_1, K_2 = derived constants indicative of the distance setting or range of the element
S = a factor indicative of the variation of the range of the GAX starting unit with applied voltage
ψ = an angle characteristic of the element at which the operating torque is a maximum

(*a*) Impedance Element

$$kI^2 = \left(\frac{V}{z_p}\right)^2 \tag{A1}$$

$$K = z_p\sqrt{k} \tag{A2}$$

$$K = \frac{V}{I} \tag{A3}$$

$$K\angle\phi_z = Z\angle\phi_z = \frac{V}{I}\angle(\phi_V - \phi_I) \qquad \text{(A4) (6)}$$

(b) Reactance Element

$$kI^2 = I\frac{V}{z_p}\sin(\phi_V - \phi_I - \phi_{zp}) \tag{A5}$$

In order for this element to indicate reactance ϕ_{zp} must be made $= 0$. If this is done

$$K = kz_p; \qquad \phi_{zp} = 0 \tag{A6}$$

$$\frac{K}{\sin(\phi_V - \phi_I)} = \frac{V}{I} \tag{A7}$$

$$\frac{K}{\sin\phi_z}\angle\phi_z = Z\angle\phi_z = \frac{V}{I}\angle(\phi_V - \phi_I) \tag{A8) (8}$$

(c) Modified Reactance Element

The construction and principle of operation of this relay is fully described in reference 5 to which the reader is referred.

$$I^2 + \left(\frac{V}{k'z_p'}\right)^2 + 2I\frac{V}{k'z_p'}\cos(\phi_V - \phi_I - \phi_{zp}) = \left(\frac{V}{kz_p}\right)^2 \tag{A9}$$

$$K_1 = kz_p; \quad K_2 = k'z_p'; \quad \psi = \phi_{zp}' \tag{A10}$$

Substitute equations $A10$ in equation $A9$ and divide by I^2

$$1 = \left(\frac{1}{K_1^2} - \frac{1}{K_2^2}\right)\left(\frac{V}{I}\right)^2 - \left(\frac{2}{K_2}\cos(\phi_V - \phi_I - \psi)\right)\left(\frac{V}{I}\right) \tag{A11}$$

Equation $A11$ is a quadratic which may be solved for V/I and the solution expressed in the polar form yields equation 10 given in the text.

(d) Directional Elements With Voltage Restraint

Two types of single-phase elements must be distinguished, the *GAX* starting unit type which employs a single voltage and current, and the *GCX* starting unit type which employs 2 voltages and a current.

1. *GAX Type.* In this element the operating torque is obtained from the current I in the current coil and the current in a potential coil which is connected to the source of potential V through a condenser (to obtain the desired phase shift) and a Thyrite stack in order to give the current in the potential coil an amplified value at low values of V. The impedance of this potential circuit z_p' is, therefore, not a constant, but is dependent upon the value of V. The power factor angle of this circuit ϕ_{zp}', however, is substantially a constant. The restraining torque is obtained from a second potential coil operating from V without amplification.

$$kI\frac{V}{z'_p}\sin(\phi_I - \phi_V + \phi_{zp}') = \left(\frac{V}{z_p}\right)^2 \tag{A12}$$

$$KS = \frac{kz_p^2}{z_p'}; \; 90° + \psi = \phi_{z'p} \tag{A13}$$

$$K\cos(\phi_V - \phi_I - \psi) = \frac{1}{S}\frac{V}{I} \tag{A14}$$

$$K\cos(\phi_z - \psi)\angle\phi_z = \frac{1}{S}Z\angle\phi_z = \frac{1}{S}\frac{V}{I}\angle(\phi_V - \phi_I) \tag{A15) (12}$$

In the above equations K is a constant indicative of the relay range at normal voltage. S is a function of V and represents the ratio of the range of the relay at any given value of V to the range at normal voltage. Figure 6 shows the relationship between S and V for the standard *GAX* relay starting unit. For a given fault condition the value of V is readily determined from the proper expression given in table I.

2. *GCX Type.* In this element the operating torque is obtained by the interaction of the current I in the current coil and the current in a potential coil which is connected to a second source of potential V_q which is in quadrature to I at unity power factor. No Thyrite stack is employed so that the impedance of this potential circuit is a constant. The restraining torque is obtained by the interaction of the current in the above mentioned potential coil and the current in a second potential coil connected to the potential V.

$$kI\frac{V_q}{z_p'}\sin(\phi_I - \phi_V - \phi_{z'p}) = \frac{V_q}{z_p'}\frac{V}{z_p}\sin(\phi_V - \phi_{Vq}) \tag{A16}$$

$$K = \frac{2}{\sqrt{3}}kz_p; \; \psi = \phi_{z'p} \tag{A17}$$

$$K\cos(90° + \phi_{Vq} - \phi_I - \psi) = \frac{2}{\sqrt{3}}\frac{V}{I}\sin(\phi_V - \phi_{Vq}) \tag{A18}$$

$$\begin{aligned} K\cos(\phi_z - \psi)\angle\phi_z &= Z\angle\phi_z \\ &= \frac{2}{\sqrt{3}}\frac{V}{I}\sin(\phi_V - \phi_{Vq})\angle 90° + \phi_{Vq} - \phi_I \\ &= \frac{V}{I}\angle(\phi_V - \phi_I) \times \frac{2}{\sqrt{3}}\sin(\phi_V - \phi_{Vq})\angle(90° + \phi_{Vq} - \phi_V) \end{aligned} \tag{A19) (13}$$

3. *Polyphase Element.* This element has 2 restraining potential coils mechanically balanced against the torque produced by a conventional polyphase directional element. The equations will be derived on the basis of the usual quadrature connections to the operating potential coils. Since we are to deal with 3 phase currents and 3 phase-to-phase voltages, these currents and voltages will be given the usual phase notation.

$$\begin{aligned} k\Big[& I_a\frac{V_{cb}}{z_p'}\sin(\phi_{Ia} - \phi_{Vcb} + \phi_{z'p}) + \\ & I_b\frac{V_{ac}}{z'_p}\sin(\phi_{Ib} - \phi_{Vac} + \phi_{z'p}) + \\ & I_c\frac{V_{ba}}{z_p'}\sin(\phi_{Ic} - \phi_{Vba} + \phi_{z'p})\Big] \\ &= \frac{V_{cb}}{z_p}\frac{V_{ba}}{z_p}\sin(\phi_{Vba} - \phi_{Vcb}) \\ &= \frac{V_{ac}}{z_p}\frac{V_{cb}}{z_p}\sin(\phi_{Vcb} - \phi_{Vac}) \\ &= \frac{V_{ba}}{z_p}\frac{V_{ac}}{z_p}\sin(\phi_{Vac} - \phi_{Vba}) \end{aligned} \tag{A20}$$

By making the substitution

$$K = 2\sqrt{3}\,k\frac{z_p^2}{z_p'}; \quad \psi = \phi_{z'p} \tag{A21}$$

and transposing the terms, the following equation is obtained.

$$\frac{K\cos(90° + \phi_{Vcb} - \phi_{Ia} - \psi)}{\frac{2}{\sqrt{3}}\frac{V_{ba}}{I_a}\sin(\phi_{Vba} - \phi_{Vcb})} + \frac{K\cos(90° + \phi_{Vac} - \phi_{Ib} - \psi)}{\frac{2}{\sqrt{3}}\frac{V_{cb}}{I_b}\sin(\phi_{Vcb} - \phi_{Vac})} + \frac{K\cos(90° + \phi_{Vba} - \phi_{Ic} - \psi)}{\frac{2}{\sqrt{3}}\frac{V_{ac}}{I_c}\sin(\phi_{Vac} - \phi_{Vba})} = 3 \tag{A22}$$

It will be noted that the 3 left-hand terms of equation $A22$ are composed of terms identical with the terms of equation $A18$ for the *GCX* unit. Substituting their equivalents from equation $A19$ the following equation is obtained:

$$\frac{K\cos(\phi_{za} - \psi)\angle\phi_{za}}{Z_a\angle\phi_{za}} + \frac{K\cos(\phi_{zb} - \psi)}{Z_b\angle\phi_{zb}}\angle\phi_{zb} + \frac{K\cos(\phi_{zc} - \psi)\angle\phi_{zc}}{Z_c\angle\phi_{zc}} = 3 \tag{A23}$$

Equation $A23$ may be reduced to the following form

$$K\cos(\phi_z - \psi)\angle\phi_z = Z\angle\phi_z = \frac{3}{\dfrac{1}{Z_a\angle\phi_{za}} + \dfrac{1}{Z_b\angle\phi_{zb}} + \dfrac{1}{Z_c\angle\phi_{zc}}} \quad \text{(A24) (14)}$$

(*e*) Type *CZ* Impedance Relay

In this type of relay the operating torque is balanced against the restraining torque through what may be considered as an ideal spring. It is apparent, therefore, that the effect of the operating torque in opposing the restraining torque is a function of the extension of the spring which in turn is a function not only of the current, but also of T, the time of application of the current. The restraining torque is produced by a voltage solenoid so constructed that the torque produced is proportional to the first power and not to the square of current in it.

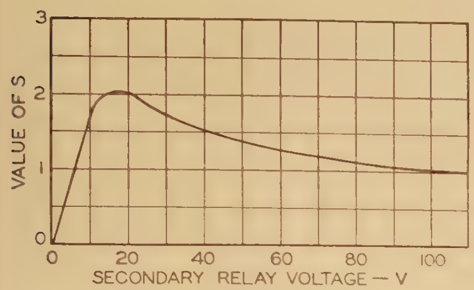


Figure 6. Variation in range of GAX starting unit with applied voltage

The relay operates when:

$$kTI = \frac{V}{z_p} \quad \text{(A25)}$$

$$K = \frac{I}{kz_p} \quad \text{(A26)}$$

$$T = K\frac{V}{I} = KZ \quad \text{(A27)}$$

Unfortunately, equation $A27$ is not satisfactory for the accurate determination of T from Z due to the fact that k and, therefore, K is not an exact constant but is affected by variations in V and I. In order to best express this variation it is desirable to write the following equations.

$$T = f\left(z_e, \frac{I}{T_c}\right) \quad \text{(A28)}$$

$$z_e = \frac{T_c}{T_v}Z \quad \text{(A29)}$$

where

T_c = the current tap setting of the relay
T_v = the voltage tap setting of the relay
z_e = an impedance which would have to be applied to the relay terminals if the relay were connected on the 1-ampere current tap and the 1-volt voltage tap to produce equivalent results

The above relationships assumed that I is a secondary current and that Z is a secondary impedance. For primary values equation $A29$ will become

$$z_e = \frac{T_cR_c}{T_vR_v}Z \quad \text{(A30) (41)}$$

where:

R_c = the current transformer ratio
R_v = the potential transformer ratio

The relationship between T and z_e for various values of I/T_cR_c can be readily determined and plotted as a family of curves. If a set of conventional CZ relay curves are available in which T is plotted against current in per cent of tap setting for various voltages applied to the relay on a given voltage tap, then the $T - z_e$ curve may be determined for a given per cent current by making use of the relationship

$$z_e = \frac{\text{voltage applied}}{T_v} \times \frac{100}{\text{per cent current}}$$

T = the time shown by the voltage curve for the given per cent current

Appendix B—Derivation of Expressions for Voltages and Currents

The expressions for voltages and currents will be derived on the basis that the positive- and negative-phase-sequence networks are identical. The following nomenclature will be used.

$\boldsymbol{E}$ = the normal primary phase to neutral voltage at the relay in the reference phase
$\boldsymbol{v}_1, \boldsymbol{v}_2, \boldsymbol{v}_0$ = the respective positive-, negative-, and zero-phase-sequence voltages at the relay in the reference phase
$\boldsymbol{V}_{0a}, \boldsymbol{V}_{ba}, \boldsymbol{V}_{ab}, \boldsymbol{V}_{ac}$ = phase-to-neutral and phase-to-phase voltage at the relay as indicated
$\boldsymbol{Z}_1$ = the equivalent impedance of the positive- (or negative) phase-sequence network expressed at the voltage $\boldsymbol{E}$
$\boldsymbol{Z}_0$ = the equivalent impedance of the zero-phase-sequence network expressed at the voltage $\boldsymbol{E}$
z = the effective positive- or negative-phase-sequence impedance between the relay and point of fault expressed at the voltage $\boldsymbol{E}$
z_0 = the effective zero-phase-sequence impedance between the relay and point of fault expressed at the voltage $\boldsymbol{E}$
z_1' = the effective positive- (or negative) phase-sequence impedance behind the relay expressed at the voltage $\boldsymbol{E}$
z_0' = the effective zero-phase-sequence impedance behind the relay expressed at the voltage $\boldsymbol{E}$
$\boldsymbol{I}_1, \boldsymbol{I}_2, \boldsymbol{I}_0$ = the respective total positive-, negative-, and zero-phase-sequence currents at the point of fault transferred to the relay and in the reference phase at the relay
$\boldsymbol{i}_1, \boldsymbol{i}_2, \boldsymbol{i}_0$ = the respective positive-, negative-, and zero-phase-sequence currents at the relay in the reference phase flowing in z or z_0
$\boldsymbol{i}_1', \boldsymbol{i}_2', \boldsymbol{i}_0'$ = the respective positive-, negative-, and zero-phase-sequence currents behind the relay in the reference phase flowing through z_1' or z_0'
$\boldsymbol{I}_a, \boldsymbol{I}_b, \boldsymbol{I}_c, \boldsymbol{I}_n$ = primary phase and neutral currents flowing through the relay with star-connected current transformers
$\boldsymbol{I}_a', \boldsymbol{I}_b', \boldsymbol{I}_c'$ = primary phase currents flowing through the relay with delta-connected current transformers
c_1 = $\boldsymbol{i}_1/\boldsymbol{I}_1 = \boldsymbol{i}_2/\boldsymbol{I}_2$
= the positive- (or negative) phase-sequence current distribution factor at the relay
c_0 = $\boldsymbol{i}_0/\boldsymbol{I}_0$
= the zero-phase-sequence current distribution factor
$\boldsymbol{A}, \boldsymbol{B}$ = factors used to simplify the expressions for the voltages $\boldsymbol{V}_{ba}$ and $\boldsymbol{V}_{ac}$

C, D = factors used to simplify the expressions for the currents I_b and I_c in the case of 2 phase-ground faults

C', D' = factors used to simplify the expressions for the currents I_a' and I_c' in the case of 2 phase-ground faults

The following equations express the phase sequence voltages at the relay in the reference phase.

$$v_1 = E - i_1'z_1' = E - (I_1Z_1 - i_1z) \quad \text{(B1)}$$

$$v_2 = -i_2'z_1' = -(I_2Z_1 - i_2z) \quad \text{(B2)}$$

$$v_0 = -i_0'z_0' = -(I_0Z_0 - i_0z_0) \quad \text{(B3)}$$

From these the following equations are derived to express the phase-to-neutral and phase-to-phase voltages at the relay.

$$V_{0a} = v_1 + v_2 + v_0 = E - (I_1 + I_2)Z_1 - I_0Z_0 + (i_1 + i_2)z + i_0z_0 \quad \text{(B4)}$$

$$V_{ba} = \sqrt{3}(v_1\angle 30° + v_2\angle -30°) = \sqrt{3}[E\angle 30° - (I_1\angle 30° + I_2\angle -30°)Z_1 + (i_1\angle 30° + i_2\angle -30°)z] \quad \text{(B5)}$$

$$V_{cb} = \sqrt{3}(v_1 - v_2)\angle -90° = \sqrt{3}[E - (I_1 - I_2)Z_1 + (i_1 - i_2)z]\angle -90° \quad \text{(B6)}$$

$$V_{ac} = \sqrt{3}(v_1\angle 150° + v_2\angle -150°) = \sqrt{3}[E\angle 150° - (I_1\angle 150° + I_2\angle -150°)Z_1 + (i_1\angle 150° + i_2\angle -150°)z] \quad \text{(B7)}$$

The phase and neutral currents in the relay may be expressed in terms of the phase sequence components in the reference phase as follows:

$$I_a = i_1 + i_2 + i_0 \quad \text{(B8)}$$

$$I_b = i_1\angle -120° + i_2\angle 120° + i_0 \quad \text{(B9)}$$

$$I_c = i_1\angle 120° + i_2\angle -120° + i_0 \quad \text{(B10)}$$

$$I_n = 3i_0 \quad \text{(B11)}$$

$$I_a' = \sqrt{3}(i_1\angle 30° + i_2\angle -30°) \quad \text{(B12)}$$

$$I_b' = \sqrt{3}(i_1\angle -90° + i_2\angle 90°) \quad \text{(B13)}$$

$$I_c' = \sqrt{3}(i_1\angle 150° + i_2\angle -150°) \quad \text{(B14)}$$

The above equations are general and apply for any type of fault. The following relationships apply for the particular case of fault under consideration.

1. *Three-Phase Fault*

$$E = I_1Z_1; \quad I_2 = 0; \quad I_0 = 0 \quad \text{(B15)}$$

$$i_1 = c_1\frac{E}{Z_1}; \quad i_2 = 0; \quad i_0 = 0 \quad \text{(B16)}$$

2. *Phase-Phase Fault (no phase shift in voltage between relay and fault)*

$$E = 2I_1Z_1; \quad I_2 = -I_1; \quad I_0 = 0 \quad \text{(B17)}$$

$$i_1 = \frac{c_1E}{2Z_1}; \quad i_2 = -i_1; \quad i_0 = 0 \quad \text{(B18)}$$

3. *Phase-Ground Fault (no phase shift in voltage between relay and fault)*

$$E = I_1(2Z_1 + Z_0); \quad I_2 = I_1; \quad I_0 = I_1 \quad \text{(B19)}$$

$$i_1 = \frac{c_1E}{2Z_1 + Z_0}; \quad i_2 = i_1; \quad i_0 = \frac{c_0E}{2Z_1 + Z_0} \quad \text{(B20)}$$

4. *Two Phase-Ground Fault (no phase shift in voltage between relay and fault)*

$$E = (I_1 - I_2)Z_1;$$

$$I_2 = -\frac{Z_0}{Z_1 + Z_0}I_1; \quad I_0 = -\frac{Z_1}{Z_1 + Z_0}I_1 \quad \text{(B21)}$$

$$i_1 = \frac{c_1(Z_1 + Z_0)}{Z_1(Z_1 + 2Z_0)}E;$$

$$i_2 = -\frac{c_1Z_0}{Z_1(Z_1 + 2Z_0)}E; \quad i_0 = -\frac{c_0}{Z_1 + 2Z_0}E \quad \text{(B22)}$$

5. *Phase-Phase Fault (30-degree phase shift in voltage between relay and fault)*

$$E = 2I_1Z_1; \quad I_2 = I_1; \quad I_0 = 0 \quad \text{(B23)}$$

$$i_1 = \frac{c_1E}{2Z_1}; \quad i_2 = i_1; \quad i_0 = 0 \quad \text{(B24)}$$

6. *Phase-Ground Fault (30-degree phase shift in voltage between relay and fault)*

$$E = I_1(2Z_1 + Z_0); \quad I_2 = -I_1; \quad I_0 = 0 \quad \text{(B25)}$$

$$i_1 = \frac{c_1E}{2Z_1 + Z_0}; \quad i_2 = -i_1; \quad i_0 = 0 \quad \text{(B26)}$$

7. *Two Phase-Ground Fault (30-degree phase shift in voltage between relay and fault)*

$$E = (I_1 + I_2)Z_1; \quad I_2 = \frac{Z_0}{Z_1 + Z_0}I_1; \quad I_0 = 0 \quad \text{(B27)}$$

$$i_1 = \frac{c_1(Z_1 + Z_0)}{Z_1(Z_1 + 2Z_0)}E; \quad i_2 = \frac{c_1Z_0}{Z_1(Z_1 + 2Z_0)}E; \quad i_0 = 0 \quad \text{(B28)}$$

Equations *B*15–*B*28 when substituted in equation *B*5–*B*7 and *B*8–*B*14 yield the expressions for voltages and currents given in table I.

Equations *B*14 and *B*20 when substituted in equations *B*4, *B*8, and *B*11 give rise to equation 43 in the text.

The vector angles between the voltages are obtained by division of the voltage expressions given in table I. In all cases:

$$\frac{V_{ba}}{V_{cb}} = -\frac{A}{2} \quad \text{(B29)}$$

$$\phi_{Vba} - \phi_{Vcb} = 180° + \phi_A \quad \text{(B30)}$$

$$\frac{V_{cb}}{V_{ac}} = -\frac{2}{B} \quad \text{(B31)}$$

$$\phi_{Vcb} - \phi_{Vac} = 180° - \phi_B \quad \text{(B32)}$$

$$\frac{V_{ac}}{V_{ba}} = \frac{B}{A} \quad \text{(B33)}$$

$$\phi_{Vac} - \phi_{Vba} = \phi_B - \phi_A \quad \text{(B34)}$$

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Tests on Oil-Impregnated Paper—II

Effects of Gas Pressure

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Synopsis

In 1934 tests were started to investigate the important factors influencing the life of oil-impregnated paper at high voltage. Last year we described the techniques developed to date in this investigation. The present paper presents all data taken on specimens tested under a gas pressure of 200 pounds per square inch and compared all results obtained with one commercial mineral oil and one commercial wood-pulp paper for 3 conditions of gas pressure. The results indicate that under the conditions of these tests *there is no correlation between dielectric loss and electrical life* and that *gas-free specimens are superior to any specimens saturated with gas up to 200 pounds per square inch pressure.*

A. Introduction

THE TECHNIQUE developed in our laboratories for studying the causes of electrical failure in oil-impregnated paper using miniature specimens has been described in an earlier paper.[1] Three types of cells were developed to allow life tests to be made under 3 conditions of gas pressure; namely, gas saturated at atmospheric pressure (figure 2), gas saturated at 200 pounds per square inch pressure (figure 4), and gas free (figure 3). This paper also showed the results obtained with 23 specimens which were saturated with gas at atmospheric pressure. It is the object of the present paper to present the data obtained on all the specimens which we have saturated with gas at 200 pounds per square inch pressure, and to compare the data obtained using one commercial mineral oil (oil *A*) and one commercial wood-pulp paper (paper *D*) for 3 conditions of gas pressure in the specimen.

The most general criticism of the work presented in the previous paper was the lack of check tests. The same criticism can be applied to the data presented in this paper since all specimens listed were made in 1934 during the preliminary stages of this investigation. Our subsequent efforts have been directed toward studying *gas-free* specimens and no check tests on the gas saturated or gas pressure specimens have been attempted. Also, we exhausted our supply of oil *A* so that no check tests with identical samples of oil and paper are now possible. However, I believe that the marked differences in life shown by figure 1 are significant and worthy of publication.

The important characteristics of oil *A* and paper *D* are shown in tables I and II.

B. Specimens Saturated With Gas at Atmospheric Pressure

Table III gives a summary of the life-test data for specimens containing oil *A* and paper *D* and maintained during life under a gas pressure of one atmosphere. All but one of these specimens failed at 22 kv in less than 150 days. Number 165, however, was raised to 30 kv at the end of 150 days and failed immediately. The power factor life history of all specimens is shown in figure 1.

C. Specimens Saturated With Gas at 200 Pounds Per Square Inch Pressure

Table IV gives a summary of the life-test data for all specimens made with 10 layers of paper *D* and maintained during life under a gas pressure of 200 pounds per square inch. Specimens numbers 182*B* and 300 were dried, impregnated and immersed with degasified oil in the pressure vessel, and then charged with gas to 200 pounds per square inch pressure. The other specimens were dried and impregnated in a glass cell and then allowed to drain while still under good vacuum. After draining, they were transferred as quickly as possible to the pressure vessel and charged with gas at 200 pounds per square inch pressure. Specimens numbers 184, 185, and 186 were drained hot while the oil-impregnated samples were drained cold so that they would retain the maximum volume of oil. The drained samples were made up so as to simulate the worst possible conditions of a high-pressure-gas cable, such as a high spot in the line from which the impregnant would gradually drain away because of temperature cycles during operation. Specimen number 188 was made to see whether 200 pounds per square inch gas pressure was sufficient to prevent ionization in unimpregnated paper. The result was quite conclusive. It was unfortunate that the pressure cell containing specimen number 300 developed a leak which was not detected until the sample had failed electrically because this specimen would probably have had the longest life of any of this series.

One very interesting observation in connection with the preparation of these specimens was the difference in absorption of N_2 and CO_2. The oil and paper became saturated with N_2 in about one hour whereas several days were

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HUBERT H. RACE is a research engineer for the General Electric Company, Schenectady, N. Y. The information reported in this paper is obviously the result of the co-operative efforts of many individuals. In particular, the author wishes to express appreciation to those who have been responsible for important phases of the work, namely: S. I. Reynolds, for preparation of specimens, preliminary and post-mortem electrical measurements; H. M. Bousman, for life tests; and Doctor E. H. Winslow, for acid and metal determinations.

1. For all numbered references, see list at end of paper.

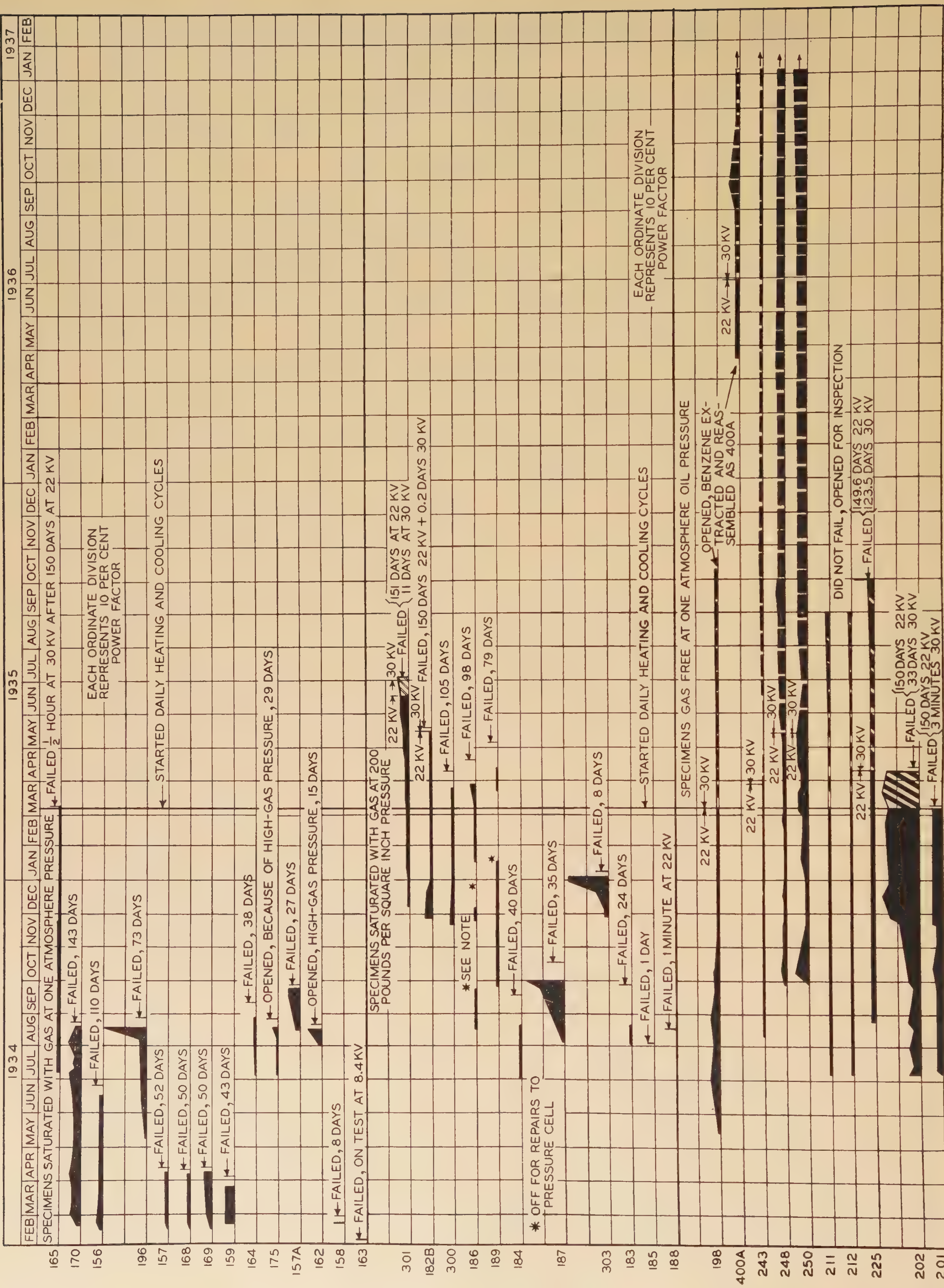

Figure 1. Life-test data

required to completely saturate the specimens with CO_2. Also the quantity of CO_2 absorbed was correspondingly very much greater.

Table V gives the data obtained by post-mortem examination of the 3 high-pressure specimens having longest life.

After specimens numbers 300 and 301 were prepared it was found that the tank N_2 used to charge them may have contained up to 1 per cent O_2. This may account for the high values of power factor, acid number, hydrophil number, and lead in solution in the oil from the latter specimen.

Table I. Properties of Oil A

Flash point	about 165 degrees centigrade
Fire point	about 185 degrees centigrade
Pour point	about −40 degrees centigrade
Specific gravity at 15.6 degrees centigrade	about 0.904
Viscosity (Univ. Saybolt) at 37.8 degrees centigrade	about 105 sec.
Iodine unsaturation number (grams per 100 grams)	about 15
Slight oxidation number	about 15
Neutralization number (milligrams KOH per gram)	≤0.015
Chlorides	None
Free sulphur	None
Power Factor at 60 cycles per second and 60 degrees centigrade	<0.0002

Table II. Properties of Paper D

Type	100 per cent sulphate kraft
Thickness	0.0065 inch ± 0.0005 inch
Apparent density	0.75
Ash content	1.2 per cent
Alkalinity (milligrams H_2SO_4 per gram)	0.1
Tensile strength strip one inch wide (machine direction)	80 pounds
Tensile strength strip one inch wide (cross direction)	22 pounds
Tearing strength (Elmendorf) machine direction	140 pounds
Tearing strength (Elmendorf) cross direction	280 pounds

By contrast, note the low values for all these quantities for the oil removed from specimen number 182*B*, which was charged with dry CO_2.

D. Specimens, Gas Free, at One Atmosphere Hydraulic Pressure

Table VI summarizes the life histories of all gas-free specimens that have been made with oil *A* and paper *D*. Specimen number 198 was the first gas-free specimen made. After it had been on high-voltage test for a total of 355 days it was taken out of its glass cell without disturbing the electrodes or the wrapping of the paper, extracted in benzene vapor for 24 hours, remounted in a new glass cell, reimpregnated and returned to test as number 400*A*. This was done to determine whether extraction of free oil with benzene and reimpregnation with new oil would improve the power factor. Since no improvement was obtained, we conclude that the materials responsible for dielectric loss in this specimen either are not benzene-soluble or are bound so tightly to the paper fibers that they cannot be washed out with benzene.

Specimens numbers 211 and 212 did not fail but were removed from test after a total life of 295 days, dissembled and examined by the micro methods described in the previous paper.[1] These are the only specimens which have been removed from test for examination before failure has started and therefore they have been included in this comparison. The papers used in these specimens had the same physical characteristics as paper *D*, the only difference being that they had been given special treatment to lower the ash content. There was no sign of incipient failures although there were dark brown stress marks on the inside of the inner layer showing the pattern of the edges of the copper threads on the inner electrode and light

Table III. Summary of Data for Specimens Saturated With Gas at Atmospheric Pressure

Specimen	Gas	Special Treatment†	Days Life 22 Kv	Days Life 30 Kv
165	Carbon dioxide	0.01 per cent *G*†	150+	0.02
170	Oxygen	0.1 per cent *H*†	143	
156	Oxygen	New oil	110	
196	Oxygen	0.1 per cent *F*†	75	
157	Carbon dioxide	New oil	52	
168	Nitrogen	New oil	50	
169	Carbon dioxide	0.1 per cent *H*†	50	
159	Oxygen	0.5 per cent *H*†	49	
164	Carbon dioxide	0.1 per cent *G*†	38	
175*	Carbon dioxide	Paper washed 24 hours	29	
157*A*	Carbon dioxide	New oil	26	
162*	Nitrogen	0.1 per cent *F*†	15	
158	Carbon dioxide	1 per cent *H*†	8	
163	Oxygen	1 per cent *G*†	0	

* These specimens indicated a gas pressure exceeding 2 atmospheres and were removed before failure and opened

† Special characters *F*, *G*, *H*, and *I* indicate polar substances of undisclosed nature used in the laboratory experiments

Table IV. Specimens Saturated With Gas at 200 Pounds per Square Inch Pressure

Specimen Number	Gas	Paper	Oil	Treatment	Days Life 22 Kv	Days Life 30 Kv
301	N_2	*D*	*A*	Drained	151+	11
182*B*	CO_2	*D*	*A*	Immersed	150+	0.2
300	N_2	*D*	*A*	Immersed	105*	
186	CO_2	*D*	Paraffin	Drained	98	
189	CO_2	*D*	*B*	Drained	79	
184	CO_2	*D*	Ceresin and beeswax	Drained	40	
187	CO_2	*D*	*E*	Drained	35	
303	N_2	*D*	*E*	Drained	35	
183	CO_2	*D*	*A*	Drained	21	
185	CO_2	*D*	Petrolatum and 20 per cent rosin	Drained	0.9	
188	CO_2	*D*	None		<1 minute	

* Cell leaked so that pressure dropped to 30 pounds per square inch. This probably caused failure

gray marks on the outside of the outer layer at the edge of the lead electrode. The results of the microanalyses on these specimens are given in table VIII.

Specimen number 225 has been included in this comparison because it was impregnated with oil similar to oil *A* but removed from the joint of an oil-filled cable in service and delivered to our laboratory in a standard reser-

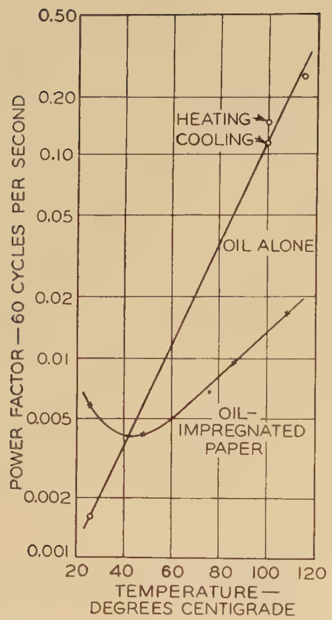

Figure 2. Comparison of power factor of used cable oil alone and cable paper impregnated with this oil under vacuum

esting in that they were impregnated with portions of oil *A*, one without and one with 0.1 per cent of a commercial oxidation inhibitor and preoxidized 96 hours at 115 degrees centigrade in a standard aging oven used by cable manufacturers for making oil-oxidation control tests. The specimen without an oxidation inhibitor gradually developed considerably higher power factor but had a longer life than the specimen containing the inhibitor (see figure 1). Neither had a life comparable with unoxidized speci-

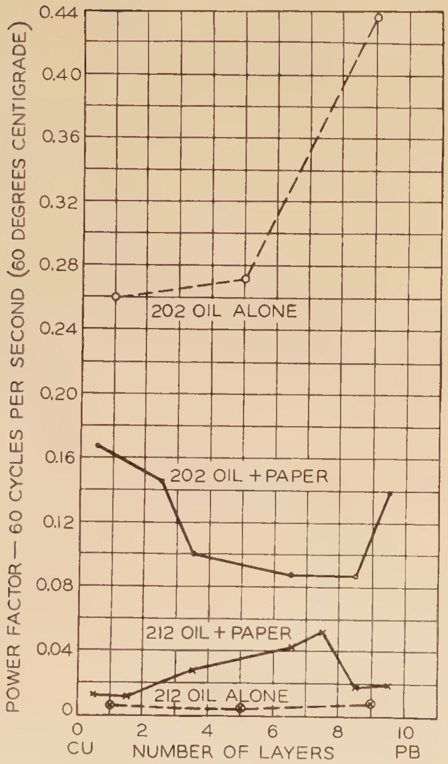

Figure 3. Radial power measurements of oil alone and oil-soaked paper from specimens 202 and 212

voir without exposure to air. The important properties of this oil which were different from those of new oil are shown in table VII. These were probably caused by contact with limited amounts of oxygen and black varnished cambric tape in the joint. The important observations from this test are the stability, relatively long life, and relatively low power factor of the specimen impregnated with this oil. That high power factor of oil does not mean correspondingly high power factor of oil-impregnated paper is shown by the life history of specimen number 225 shown in figure 1 and the comparison of oil alone and oil-impregnated paper shown in figure 2.

Specimens numbers 201 and 202 are particularly inter-

Table V. Data From Examination of Specimens Saturated With Gas at 200 Pounds Per Square Inch Pressure

Specimen		182 *B*		300		301	
Days life, 22 kv		150+		105		151+	
Days life, 30 kv		0.2		0		11	
Oil		A		A		A	
Paper		D		D		D	
Gas		CO_2		N_2		N_2	
Pressure (pounds per square inch) at 60 degrees centigrade		250		215		225	
	Portion	ϵ'	**P. F.**	ϵ'	**P. F.**	ϵ'	**P. F.**
Test 1 Paper plus oil Dielectric constant (ϵ') and power factor (P. F.)	1	2.78	0.097	2.49	0.068	3.67	0.200
	2	2.13	0.039	2.79	0.053	3.46	0.175
	3	2.69	0.020		0.040	3.37	0.132
	4	2.65	0.025	2.79	0.057	3.46	0.160
	7	2.56	0.012			3.54	0.152
	8		0.017			3.47	0.164
	9	2.84	0.010			3.59	0.190
	10	3.12	0.055			3.62	0.265
Test 2 Oil. Dielectric constant (ϵ') and power factor (P. F.)	1	2.16	0.0036	2.18		2.07	0.250
	2	2.16	0.0019	2.16	0.045	2.06	0.237
	3	2.17	0.0019	2.16	0.042	2.07	0.278
Test 3 Acid (Milligram per gram)	1	0.1		0.3		0.5	
	2	<0.1		0.1		0.3	
	3	<0.1				0.3	
Test 4 Hydrophil (Square centimeters per milligram)	1	30		83		276	
	2	23		68		261	
	3	26		81		253	
Test 5 Molecular weight (Grams per mol)	1	335	275	270	256	332	256
	2	270	304	184	314	294	284
	3	313	303	309	313	265	208
Test 6 Unsaturation (Grams per 100 grams)	1	0		9		8	
	2	0		9		4	
	3	0		15		7	
		Cu	Pb			Cu	Pb
Test 7 Copper and lead (10^{-6} grams per gram)	1	*	*			*	30
	2	*	*			*	50
	3	*	*			*	380

* Less than minimup detectable concentration.

Table VI. Specimens, Gas Free, at One Atmosphere Hydraulic Pressure Containing Oil A and Paper D

Specimen Number	Special Treatment	Days Life 22 Kv	Days Life 30 Kv
198	(First gas-free specimen made)	186+	169+
400*A*	Number 198 extracted with C_6H_6 and re-impregnated	31+	151+
243	Paper washed 24 hours in tap water	149+	446+
248	Oil filtered through fullers' earth	156+	418+
250	Same as number 248	156+	418+
211	Special-low-ash paper	149+	146*
212	Special low ash paper	149+	146*
225	Used oil from oil-filled cable in service	150+	123
202	Oil *A* oxidized 96 hours at 115 degrees centigrade	149+	33
201	Oil *A* + 0.1 per cent oxidized 96 hours at 115 degrees centigrade	149+	3 minutes

* Opened for inspection—did not fail

mens (198, 401, 211, 243, 248, 250). Apparently, although a cable may contain no free oxygen, if the oil has been oxidized before it is used to impregnate a cable, chemical reactions thus started continue during the life of the cable to the detriment of its electrical properties.

Table VIII shows the results of micro examinations which were made on gas-free specimens shown in table VI. Specimens for which no analysis is given are still running. Tests 4–7 are not reported because the measurements were made several days after the specimens were opened and the results are questionable. It is interesting to note that the specimens containing preoxidized oil showed measurable neutralization numbers concentrated at the electrodes whereas the unoxidized oils had neutralization numbers below our ability to measure them when these specimens were opened. Since these measurements were made the sensitivity of the acid and soluble metal measurements has been considerably improved. The technique will be described in later papers when more experience has been gained with the new methods.

The major difference between specimens 202 and 212 is that the oil used in number 202 was preoxidized before degasification and filling. Therefore, it is very interesting to compare the electrical data shown in figure 3 taken after these 2 specimens were opened.

The oil removed from specimen number 212 showed low losses throughout. The oil-soaked paper from specimen number 212 showed higher losses in the center and lowest at both the copper and lead ends. A plausible explanation for this variation is that *in the absence of oxygen or oxidation products* there was negligible chemical action at the 2 electrodes but that some thermal deterioration occurred in the center layers where the temperature would be highest because of dielectric losses. Now considering specimen number 202 the findings are entirely different. The oil extracted from the paper shows very high losses, particularly at the lead end. The oil-soaked paper gives a power factor curve similar to that observed in commercial cables,[2] being higher in the layers closest to the copper core and lead sheath and lowest in the center layers away from the metal electrodes. These data indicate that oxidized oil is the cause of this type of results observed in tests on commercial cable.

Table VII. Measurements on Sample of Oil Removed From Cable Joint in Service and Used to Impregnate Specimen Number 225

Power factor at 26 degrees centigrade	0.0017
Power factor at 100 degrees centigrade	0.115
Power factor at 115 degrees centigrade	0.245
Neutralization number (grams KOH per milligram oil)	0.037
Hydrophil number (square centimeters per milligram oil)	6.1

E. Conclusions

The following general conclusions seem justified by the data presented in this paper.

1. At high electric stress, *gas-free*, oil-impregnated paper at one atmosphere oil pressure (oil and paper having properties like the components of oil-filled cable) should have longer life and less tendency to fail by gaseous ionization than similar cable under N_2 or CO_2 gas pressure up to at least 200 pounds per square inch gas pressure

2. High power factor of oil-impregnated paper does not necessarily mean short life as long as temperature equilibrium is maintained

3. The presence of oxidized oil will cause high dielectric losses, particularly in the layers of paper near the metal electrodes

Table VIII. Data From Examination of Gas-Free Specimens

Specimen		201		202		211		212		225	
Days life, 22 kv		149+		149+		149+		149+		150+	
Days life, 30 kv		3 minutes		33		146+		146+		123	
Oil		*A* + *F*		*A*		*A*		*A*		Used oil	
Paper		*D*		*D*		*J*		*K*		*D*	
		oil oxidized 96 hours at 115 degrees centigrade									
Test 1	Portion	ε′	P. F.	ε′	P. F.	ε′	P. F.	ε′	P. F.	ε′	P. F.
Paper plus oil (ε′ and power factor)	1	3.23	0.168	2.98	0.017	3.29	0.013	3.01	0.048		
	2			3.03	0.020	3.30	0.012	2.91	0.040		
	3	3.36	0.146	3.03	0.017	3.22	0.020	3.29	0.047		
	4	3.21	0.101	2.97	0.011	2.99	0.028	3.37	0.047		
	7	3.02	0.088	3.06	0.018	3.08	0.043	3.27	0.048		
	8			3.13	0.044	3.16	0.053	3.21	0.046		
	9	3.68	0.087	3.03	0.039	3.20	0.018	3.23	0.044		
	10	3.42	0.138	2.88	0.018	3.11	0.020	3.05	0.044		
Test 2, Oil (ε′ and power factor)	1	2.18	0.260	2.18	0.018	2.16	0.006	2.18	0.047		
	2	2.17	0.274	2.18	0.016	2.16	0.004	2.20	0.046		
	3	2.17	0.436	2.18	0.011	2.16	0.008	2.20	0.047		
Test 3, Acid (milligrams per gram)	1	0.1		0.2		<0.1		<0.1		0.02*	
	2	<0.1		<0.1		<0.1		<0.1		0.02*	
	3	0.2		0.1		<0.1		<0.1		0.01*	

* These measurements were made with a recently developed, more sensitive neutralization number technique.

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Distortion of Traveling Waves by Corona

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Synopsis

In order to make possible the prediction of the attenuation and distortion of lightning waves on transmission lines an equation is proposed that relates the change of shape of a traveling wave to the corona loss on the line at normal operating frequency. Results obtained by computation from this formula are compared with experimental results of various investigators.

THE ATTENUATION of high-voltage traveling waves by corona is of importance because of the protection it affords to terminal equipment when lightning strikes a transmission line at some distance from the nearest transformer station. The traveling wave that results from the lightning discharge has been found by many observers to lose energy quite rapidly as long as its crest voltage is well above the corona-forming voltage of the line on which it travels. A line of several miles length may usually be depended upon, therefore, to reduce the initial voltage of the lightning wave to a safe value.

Various equations have been proposed to express the rate of attenuation of the wave. These are reviewed by Bewley.[3] All of them, including an equation proposed by one of the present authors,[2] are purely empirical and have one or more adjustable constants which cannot be predetermined. It is now proposed to relate the distortion and attenuation of a traveling wave to the loss of power in corona at the line's normal operating frequency.

The Mechanism of Corona Loss

The energy loss that accompanies corona is due to motion of free electric charge in the space surrounding conductors at high potential. This was pointed out by Ryan and Henline[4] in 1924, and the study of space charge which has since been carried on leads to the following conclusions:

1. There is a critical electric gradient for air that cannot be exceeded. Any attempt to increase the gradient above the critical value results in profuse ionization of the air, and the charges liberated by ionization take up such positions in space that the gradient is maintained at (or below) the critical value

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The analytical work reported in this paper is by H. H. Skilling. The experimental work was done by P. de K. Dykes, while a graduate student at the Ryan Laboratory, Stanford University. The aid of Doctor J. S. Carroll, director of the Ryan Laboratory, is gratefully acknowledged.

1. For all numbered references, see list at end of paper.

2. Shortly after its formation space charge becomes relatively immobile. This is doubtless due to the formation of relatively heavy ions, for which the mobility is almost negligible as compared to electrons

3. The supply of space charge to the region about a conductor commences when the critical gradient is reached, and continues as long thereafter as the applied voltage continues to increase. During this time there is loss of energy from the conductor

4. After the crest of a voltage wave is reached, and the voltage begins to decrease, the space charge remains (approximately) constant in magnitude and fixed in position. During this time there is little loss of energy from the conductor, what loss there is being due to diffusion of the ions in the electric field at a slow rate. This interval ends when the critical gradient of opposite sign is reached and a new interval of active ionization commences

Space charge may be considered as forming a protective sheath about a conductor—a sheath that receives and terminates much of the incoming dielectric flux, so that no part of the air about the conductor is subjected to electric stress greater than the critical value. If voltage were raised so that the electric stress at any point exceeded the critical value, the gradient at the overstressed point would immediately be reduced by further ionization and the production of additional protective space charge. The action is analogous to the relief of mechanical stress in a piece of overstressed steel by inelastic deformation of the material.

When the voltage applied to a conductor is alternating it is necessary to locate a protective sheath of space charge about the conductor as the voltage rises to a crest, and then to neutralize that charge and replace it with one of opposite sign as the voltage changes to a crest of opposite polarity. Energy is consumed in the production of the space charge; the amount of energy consumed per cycle depends on the crest voltage of the wave but, as the amount of space charge required is independent of the duration of a cycle, the energy per cycle consumed in its production is independent of the frequency of the applied voltage. The power, consequently, or energy per second, is proportional to frequency. But this is not the total loss.

There is another kind of loss that is due to migration of the ions of space charge in the electric field. The protective sheath of space charge can never be stationary, for it is at all times acted upon by the electric field of the applied voltage and that of other parts of the space charge. When space charge moves in response to the electric field of the applied voltage it consumes power. So there is a continuous drain of power due to the *motion* of the space charge, quite apart from that due to its *formation*. Both are dependent upon the amount of applied voltage, but the loss due to migration differs from that due to formation by being a nearly constant loss that (at low frequency) is independent of the frequency. At moderately high fre-

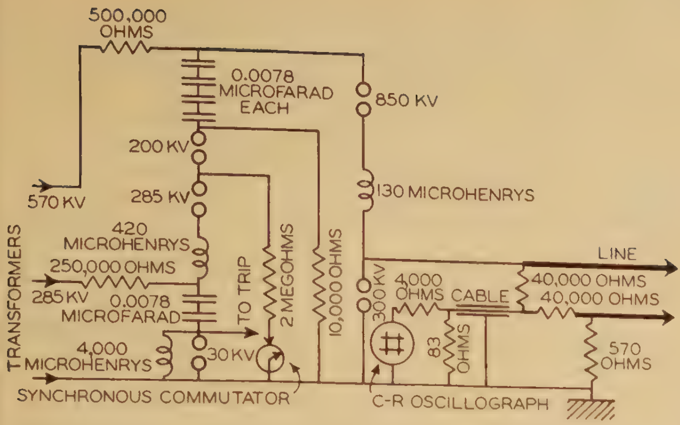


Figure 1. Impulse generator and oscillograph

quencies it becomes a negligible part of the total loss, while at 60 cycles per second it is about one-third of the total.[5]

The energy required to produce a protective sheath of space charge about a conductor is dependent upon the height to which the applied voltage rises. Each increase of voltage requires an increase of space charge, with a corresponding consumption of energy. As the applied voltage is raised from e to $e + \Delta e$ the energy which has been used to produce space charge increases from E to $E + \Delta E$. The ratio of the increments is (for very small increments) dE/de, which may be found by differentiation. The loss corresponding to a given increment of voltage is of course not constant, but is in general greater when the increase of voltage takes place at a high voltage than when the same increase takes place at a low voltage.

In developing the above concept of corona loss the mechanism of corona formation has been greatly idealized, and many small factors have been entirely neglected. One of these is a difference in loss on the positive and negative half-cycles of corona. This particular factor requires special mention, for it will arise again in the discussion of traveling waves.

Loss From a Traveling Wave

A wave of electric energy traveling along a transmission line will necessarily produce ionization about the line as it passes and, since the only source of energy is the wave itself, it will lose energy as it travels. There is ample direct evidence of corona produced by traveling waves, for it may be both seen and heard.

Moreover, the voltage of a wave is related to its energy, although the relationship is not at all simple in a wave which is changing in shape as it travels. On a line without loss, or a distortionless line, energy is proportional to the square of the voltage for each element of the wave. This simple relationship is an approximation when applied to waves that are producing corona, but under any circumstances the voltage of a wave becomes less as its energy is decreased. And oscillographic measurements and sphere-gap measurements both show a rapid reduction of the voltage of traveling waves as long as their voltage exceeds the corona-forming voltage of the line.

Analysis of Oscillograms

Oscillograms of waves attenuated by corona are shown in figure 2. The figure shows at the top, left, the record of a 320-kv wave impressed upon a line of number 10 copper wire, and at the top, right, the record of the same wave as it was received after traveling 836 feet along the line. Below this is a similar record of a wave of negative polarity, with an equal initial voltage but showing rather less attenuation as received. The time scale of the record is given by the 5-million-cycle wave at the bottom of the figure; the initial waves rise from zero to maximum voltage in 0.3 microseconds, the wave fronts being practically straight lines. These are typical of a collection[1] of several dozen of such oscillograms.

The network shown in figure 1 was used in obtaining these records. In producing a wave, the sphere gap set to flash at 285 kv is first to trip, the polarity of discharge being determined by a synchronous commutator. This immediately actuates the trip circuit of the cathode-ray oscillograph, and then, with a slight time delay, because of inductance, the gap set for 200-kv sparks. One set of condensers is charged by the transformers to 285 kv, and the other set to 570 kv; operation of the first 2 sphere gaps connects the condensers in series and so trips the main gap which is set at 850 kv. The condensers now commence to discharge into the line, producing the test surge, but when the voltage across the line has risen to 300 kv the surge is "chopped" by a sphere gap, and the surge voltage drops almost immediately to zero.

By adjusting the values of inductance, waves were produced having wave fronts of 0.3 to 1.63 microseconds duration. All waves were substantially triangular in shape. The oscillograms show a superimposed ripple, but this originated in the oscillograph circuit; it could be removed by introduction of damping resistance in the oscillograph circuit, but it was found best not to do so because of resulting loss of accuracy of the record.

The generated surge was sent out as a traveling wave on the test line. The line was laid out as a large loop, returning to the laboratory, and terminated in a resistor having the surge resistance of the line. Both outgoing and returning waves were recorded on a cathode-ray oscillograph.

Examination of the oscillograms yields the following information. The received wave has a wave front that is less steep than was that of the initial wave. The time re-

Figure 2. Oscillograms of traveling waves, showing distortion by corona

quired for the received voltage to rise from zero to maximum is equal to the time required for the initial voltage to rise from zero to maximum and then to descend to a value equal to the maximum received voltage. In other words, if the received wave were superimposed on the initial wave its crest would fall upon the "tail" of the initial wave, as shown in figure 3. At the same time the received wave has acquired a longer tail than was possessed by the initial wave. The appearance of the whole is as if the wave front had been cut down to a gentler slope as a result of having traveled along the line, so that the front and crest of the wave have been reduced, while the tail has somewhat gained.

Various attempts to deduce a law of action by *a posteriori* reasoning from the oscillograms failed, but they served at least to indicate the nature of the differential equation from which the law would have to be derived. It was seen to be related to the "quadratic law" of corona loss as promulgated by Peek,[5] and so the quadratic law was adopted as a starting point for the *a priori* deduction of a law of distortion by corona.

Deduction of a Law of Action

Power loss from the experimental transmission line was determined by measurement, and is shown in figure 4. By plotting on a logarithmic scale it was found that the curve may well be expressed analytically as

$$\text{Loss} = k'(e - e_0)^2 \tag{1}$$

in which e is voltage, and e_0 and k' are constants. The constants as so determined are in good agreement with those computed from the coefficients of Peek's law.

Corona loss is measured as power; that is, as energy per second. After that part of the power loss which is not proportional to frequency has been subtracted, the remainder may be divided by the number of voltage crests per second, and by the length of the line. The result, loss per unit length per half cycle, is expressed by an equation similar to equation 1 but with a different value for the coefficient which (for reasons that will appear later) may be written as k/n:

$$(\text{Loss as voltage rises to } e) = \frac{k}{n}(e - e_0)^2 \tag{2}$$

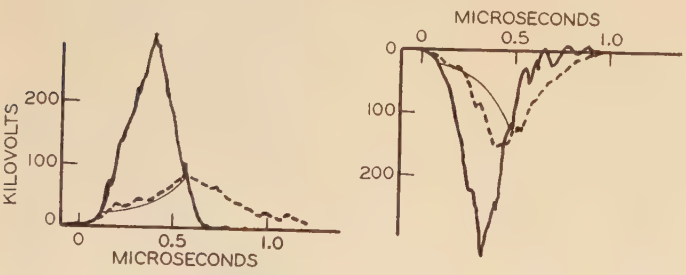


Figure 3. Initial and received waves of oscillograms, superimposed. Computed curves are also shown

The rate of energy loss as voltage increases is then found by differentiating equation 2:

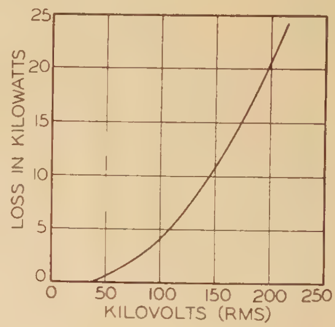
$$\frac{dE}{de} = 2\frac{k}{n}(e - e_0) \tag{3}$$

so that for a differential increase of voltage the loss is

$$dE = 2(k/n)(e - e_0)de \tag{4}$$

When an electric wave is traveling on a line the voltage at a point of the line rises as the front of the wave passes. During the passage of the wave front, space charge is placed about the conductor, and energy is lost from the wave. Consider a specific point of the line P at a distance which may be called s from some stationary reference axis. (See figure 5.) Consider a short section of the traveling wave at the point P, which section of the wave may be specified as being at a distance x from a reference axis which is moving along the line at the speed of the traveling wave. It follows that for a given point on the line s is constant, while for a given section of the wave x is constant. The 2 systems of co-ordinates are related by $s = x + y$. By definition, then, y is the distance between the reference axes, so $y = vt$ wherein v is the velocity of propagation of the wave (practically that of light) and t is the time that has elapsed since y was zero.

Figure 4. Corona loss from a number 10 American wire gauge copper conductor, 836 feet long, 12.5 feet above ground. Voltage: 60-cycle sine-wave, wire to ground



The energy loss at the point P from a section of wave of length dx while the wave is traveling a short distance dy is

$$\text{Loss} = 2\frac{k}{n}\,dx\,(e - e_0)\,de \tag{5}$$

in which de, the change of voltage at the point P, is

$$de = \frac{\partial e}{\partial x}dx + \frac{\partial e}{\partial y}dy$$

But since at a fixed point s is constant, $dx = -dy$ and

$$\text{Loss} = 2\frac{k}{n}\,dx\,(e - e_0)\left(-\frac{\partial e}{\partial x}dy + \frac{\partial e}{\partial y}dy\right) \tag{6}$$

It is now necessary to express energy of a section of traveling wave in terms of voltage. In the absence of distortion the energy of a section of wave of length dx would be

$$E = c\,dx\,e^2 \tag{7}$$

c being the capacitance per unit length of line. Half of the energy is in the electric field, and half in the magnetic.[13] When distortion of the wave is taking place this equation

becomes an approximation only. Although of uncertain accuracy in the presence of corona, it will nevertheless be used in the following discussion, for it must be of the right order of magnitude.

Differentiation of equation 7 gives the rate of change of energy of a section of wave as its voltage changes, so the change of energy corresponding to a differential change of voltage is

$$dE = 2\,c\,dx\,e\,de \tag{8}$$

But loss due to corona, as expressed in equation 6, must be supplied from the energy of the wave, so

$$2\,c\,dx\,e\,de = 2\frac{k}{n}\,dx\,(e-e_0)\left(\frac{\partial e}{\partial x}-\frac{\partial e}{\partial y}\right)dy \tag{9}$$

Since de of equations 8 and 9 is the change of voltage of a section of the wave it is the partial differential with constant x, and is equal to $(\partial e/\partial y)\,dy$. Introducing this into equation 9, and performing obvious simplifications,

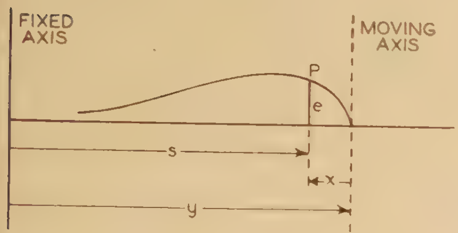


Figure 5. Coordinates of traveling wave

$$c\,e\frac{\partial e}{\partial y} = \frac{k}{n}(e-e_0)\left(\frac{\partial e}{\partial x}-\frac{\partial e}{\partial y}\right) \tag{10}$$

Rearrangement gives the partial differential equation

$$-\frac{k(e-e_0)}{k(e-e_0)+nce}\frac{\partial e}{\partial x}+\frac{\partial e}{\partial y} = 0 \tag{11}$$

for which the solution is an arbitrary function

$$f\left(t-\frac{k(e-e_0)+nce}{ncve}s,\ e\right) = 0 \tag{12}$$

(Elimination of x and y between equations 11 and 12 has been accomplished by use of the expressions defining s and y.)

The form of function to be used in equation 12 is determined by some known relationship between e and t at some known value of s; for example, at the point where the voltage wave is applied to the line. If the initial wave is the function of time $e = f_0(t)$, it follows from equation 12 that at a distance s the wave will have become

$$e = f_0\left(t-\frac{k(e-e_0)+nce}{ncve}s\right) \tag{13}$$

The initial voltage as a function of time may also be expressed $t = F_0(e)$, and corresponding to this is the equation (derived from equation 13) which applies at distance s:

$$t = F_0(e)+\frac{k}{ncv}\frac{(e-e_0)}{e}s+\frac{s}{v} \tag{14}$$

Use of Derived Equation

This form of the equation is easily applied to any traveling wave. The only information regarding the wave that is needed is a curve of voltage and time; an oscillogram, that is, of the initial voltage (or if this is not available, of the voltage at any point on the line). There is no necessity to express $f_0(t)$ or $F_0(e)$ analytically, for the equation has been arranged to allow a graphical solution. The equation gives the information that at a point at distance

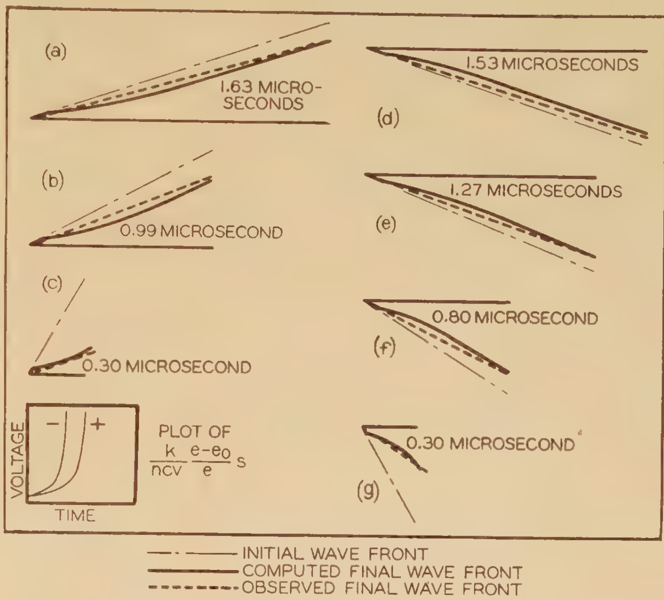


Figure 6. Comparison of computed and recorded waves after attenuation and distortion by corona. All initial waves have crest voltage approximately 310 kv

s there will correspond to each value of voltage e a value of time t. This will differ from the value of time that corresponded to the same voltage at the initial point on the line by the last term of equation 14, which is merely the time required for the wave to travel the distance s, and by the next-to-last term which alone describes the distortion of the wave due to corona.

To determine the shape of the wave at distance s, plot the initial voltage-time curve. Then, at each value of voltage increase the value of time by an amount $Ks(e-e_0)/e$. The result is the wave as distorted by corona. (It must be noted, however, that this procedure applies only on the front of the wave, while the voltage is rising to a higher value than it has before attained. In the absence of further information it must be assumed that the tail of a wave is not affected by corona. This will be discussed in a later paragraph.) Reference to equation 14 gives a value of k/ncv for K.

Symbols have the following meanings:

t = time in seconds
e = voltage in volts
e_0 = corona-starting voltage in volts (crest)
c = capacitance of the line in farads per foot
v = velocity of the wave in feet per second (practically 0.985×10^9)

s = distance of travel in feet

k = the constant of equation 2 which relates crest voltage in volts to energy loss in joules per foot per half cycle, and which may be found from Peek's quadratic law or otherwise

n = a factor which differs for positive and negative waves, and as discussed below

The Factor n

The factor n is a more or less constant factor which is needed to account for 3 differences between the corona of traveling waves and the corona at power frequency. These are (1) the effect of mobility of charge, (2) the fact that when voltage is alternating there is space charge left over from one half cycle to the next, and (3) the difference between positive and negative corona.

The effect of mobility of charge has already been mentioned; at power frequency there is considerable loss due to mobility that is essentially constant regardless of frequency. Peek[5] shows that this is 25/85 of the 60-cycle loss. Other investigators give a slightly higher value, and it will be approximately correct to consider that the loss at 60 cycles due to cyclic reversal of space charge is 2/3 of the total loss. It was partly to take care of the division of power loss into cyclic and constant parts that the factor n was introduced, and this consideration alone gives n a value of 3/2. (See equation 2.) But this value of n may be altered to take care of other considerations also.

Each crest of alternating voltage leaves the conductor surrounded by a sheath of space charge. Some of this returns to the conductor from which it came, some reaches the other conductor or is lost in space, but most remains until it is cancelled by a discharge of opposite sign as the applied voltage is reversed. During each half cycle of voltage, therefore, it is necessary not only to supply space charge of the same polarity as the voltage, but also to remove (or cancel) space charge of the opposite polarity. Consequently the total loss per half cycle is greater than would be the loss if there had been no previous opposite charge by a factor of uncertain magnitude that is something between 1 and 2. The use of n may be extended to care for this factor, and the value of n therefore becomes approximately 3.

Moreover, it is found that the loss of energy from a positive conductor is greater than that from a negative conductor. This is observed even with alternating voltage, although in the steady state the loss is largely equalized by the production of a rectified space charge. It is impossible for the charge that escapes from a conductor in corona to be continuously unbalanced, for the resulting excess of charge of one sign will accumulate until the voltage gradient about the conductor is so adjusted that the production of charge on alternate half cycles is equalized. But many observers of impulse voltages and traveling waves have found that the loss is greater from a positive conductor. It is, of course, natural that there should be a difference due to polarity because of different details of action of positive and negative ions. The ratio of loss from a positive wave to loss from a negative wave appears to be about 3 to 2. It is helpful, therefore, to assign different values to n for positive and negative waves; n^+ (for positive waves) would on this basis be about $2^1/_2$, while n^- (for negative waves) would be about 4.

Comparison With Oscillograms of Waves

In figures 3, 6, 8, and 9 a comparison is shown of distortion as predicted by equation 14 and actual oscillographic voltage records. The oscillographic curves of figure 3 have been described above; superimposed on them are computed curves based on equation 14. The values of n used in making the computations were $2^1/_2$ and 4 for positive and negative waves, respectively. These are the predicted values of n, and they give reasonably good agreement.

Figure 6 shows a comparison with the fronts of the same waves and with longer ones also. Each curve shows the average of data from several oscillograms; in most cases 5 or 6 photographic records were averaged. The term from equation 14 that expresses wave distortion due to corona is plotted in the lower left corner of the figure: in computing the shape of the distorted wave the abscissas of the appropriate curve are added to the values of time of the initial wave front, at the corresponding value of voltage.

It will be seen that agreement with measured waves is within the probable experimental error. However, computation for this figure was done with $n^+ = 4$ and $n^- = 6$, which values are about 50 per cent higher that the predicted ones.

It was also possible to compare the results of computation with equation 14 to data obtained some years ago.[2] A series of measurements with sphere gaps gave crest values of very short traveling waves as they were attenuated by corona. Only maximum voltages were measured, so the comparison must necessarily be with computed maximum values. It is known that the waves employed in the experimental work had practically uniform rise of voltage from zero to maximum, at which point they were "chopped," so that they were essentially triangular waves without tails. The slope of the impressed wave front was of the order of 2,000 kv per microsecond, and the crest voltage varied from 100 to 220 kv, so the duration of the wave is computed to be from $^1/_{20}$ microsecond for the short waves to $^1/_{10}$ microsecond for the longer ones. It will be seen that these are of a shorter order of magnitude than the waves of figure 6. Comparison of experimental and computed results is shown in figure 7; the agreement is surprisingly good. The value of n used for the computed curves was 5, but the polarity of the experimental waves is not known.

The line used for the data of figure 7 was similar in size and height to that used later, so its loss at 60 cycles was taken from figure 4. Its total length was 1,000 feet but the first 500 feet were most significant and data for that part of the line only are shown in figure 7. The complete experimental curves appear in figure 1 of a previous paper,[2] and agreement with computed values is good throughout.

For comparison with completely independent experi-

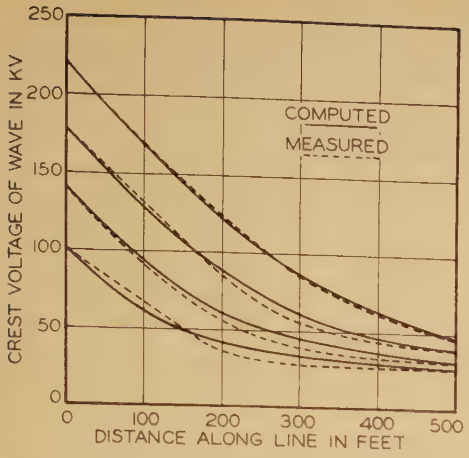


Figure 7. Comparison of computed and measured wave crests as traveling waves are attenuated by corona

mental work, computations were made of the change of shape to be expected in waves on one wire of the S-19 line of the Consumers Power Company (Michigan). Dimensions of the line are given in a paper[8] by McEachron, Hemstreet, and Rudge; corona loss on the line was computed according to the quadratic law, and the change of shape as predicted for traveling waves by equation 14 was determined on that basis. The experimentally recorded distortion of waves on the S-19 line is shown in a paper[7] by Brune and Eaton, and one set of their oscillograms is particularly fitted for comparison with computed distortion. Experimental and computed waves are shown in figure 8. The initial wave is shown, and also the received waves at 3 different distances along the line.

In computing distortion of the negative wave of figure 8*a*, a value of 4 was used for n^-, and for the positive wave of figure 8*b* a value of $2^1/_4$ was taken for n^+. See table I.

The general form of the computed and observed wave fronts of figure 8 is quite comparable. It is not at all surprising that there is difference of detail, for the computed curves consider only the effect of an ideal distribution of corona and completely neglect resistance of line and ground, the presence of other conductors, insulators and towers, variation of ground level, and other irregularities of the line. It is natural that the shorter the distance of travel, and the more rapid the attenuation by corona, the better is the agreement.

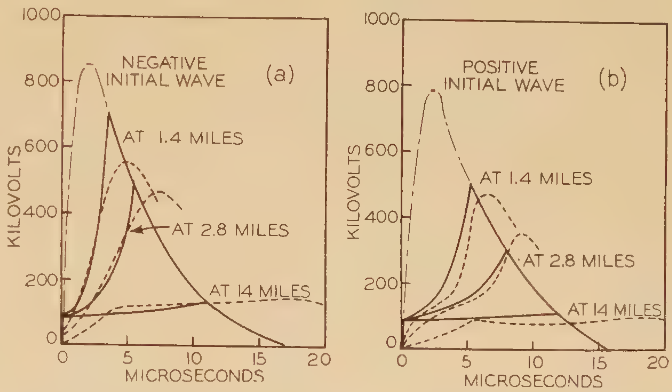
Several of the other curves shown by Brune and Eaton offer further interesting comparisons, but will not be reproduced here.

A study of the change of shape of traveling waves on the Bushkill-Roseland line of the Public Service Electric and Gas Company (New Jersey) is reported by Cox and Beck[9] and by Conwell and Fortescue.[10] The latter paper gives data that make possible the computation of corona loss at power frequency (using the quadratic law) and both papers show a number of oscillograms of waves affected by corona. Comparison of a wave from the latter paper with a curve of wave form computed from line dimensions appears in figure 9. The agreement is seen to be satisfactory. The value of n^+ used in computation was $2^1/_2$. There are several other sets of oscillograms of waves in these papers for comparison with computed distortion, but unfortunately there are no records of waves of negative polarity.

Behavior of waves on the Bushkill-Roseland line is of particular interest because it is typical of 220-kv lines in general dimensions, and therefore in corona loss. The conductors are 795,000-circular-mil-steel-reinforced aluminum cables, some 60 feet above ground. Conductors are spaced 28 feet, 6 inches, in a horizontal plane.

It will be noted that in all cases of comparison the agreement of recorded and computed distortion is good, but that different values of the factor n have been employed. The values used for n are shown in table I.

It is not improbable that the apparent variation of n with duration of wave front is entirely fictitious, being due to experimental difficulty. On the other hand, it may be due to an actual decrease of loss when the duration of the wave front under consideration is very short. If the decrease of loss is real it may be due to inability of ions to move with great enough speed, although this is improbable because the motion required for the formation of space charge is largely electronic and electrons in a critical field travel several meters per microsecond; it may more probably be attributed to ground resistance



Figures 8a (left) and 8b (right). Comparison of computed waves (solid lines) with oscillograms by Brune and Eaton (dash lines) as a traveling wave is distorted and attenuated by corona

and a consequent decrease of gradient about the conductor due to what may be loosely spoken of as a lowered equivalent ground plane.

Imperfect agreement of the values determined for n^+, and for n^-, is not at all surprising when it is remembered that the duration of the waves varies from about 10 microseconds for Brune and Eaton's waves to less than $^1/_{20}$ microsecond for Skilling's, or a factor of over 100 to 1, and that a half cycle at 60-cycle frequency is nearly 1,000 times the duration of the waves of Brune and Eaton. It appears, on the contrary, that there must be some element of truth in the theory proposed since the discrepancy in n is less than a factor of 2 over a time range of 1 to 100,000, particularly considering that the crest voltage varied from 100 kv (Skilling) to 900 (Conwell and Fortescue), the line from a number 10 wire (Dykes and Skilling) to a one-inch aluminum cable (Conwell and Fortescue), and the distance of travel from 50 feet (Skilling) to 2.8

miles (the greatest distance for really significant comparison with Brune and Eaton).

The "Tail" of the Wave

While the front of a wave is passing a short section of line it is surrounding that section with a sheath of space charge. This reduces the potential gradient in the immediate vicinity of the conductor. But after the crest of the traveling wave has passed, and the line voltage has dropped to well below its instantaneous maximum, there will be some return of space charge to the conductor. Because of the presence of space charge, the gradient about the conductor will be reversed in polarity even before the wave has completely passed, and it is this that will return some of the inner part of the charge to the conductor. As the charge returns, the tail of the passing wave is built up and lengthened. This effect is visible in all oscillograms. (See figures 3, 8, and 9.) Whether an important part of the energy of the wave is thus regained depends on the shape of the wave and the relation of its maximum voltage to corona-forming voltage of the line. In general the tail of the wave is not *greatly* altered from point to point of the line. It will be seen from any of the oscillograms that voltage at a given point on the tail is continuously but slowly increasing, but that the total increase is small compared to the crest voltage of the initial wave. It seems entirely practicable, therefore, to neglect any change of the tail in computing the change of shape of a traveling wave.

This is done in figures 3, 6, 8, and 9. It will be seen that the wave form at any point of the line is determined by extending the computed curve (based on equation 14) until it intersects the initial wave, and thereafter following the tail of the initial wave. This does not give an accurate representation of the tail of the distorted wave, but it does give a satisfactory curve for the front of the wave and a good approximation of the wave's maximum voltage. It is this last value that is usually of greatest practical importance.

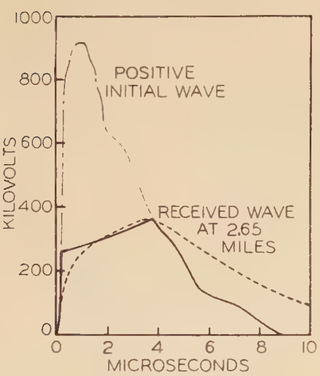


Figure 9. Comparison of computed wave (solid line) with oscillogram by Conwell and Fortescue (dash line) as a traveling wave is distorted and attenuated by corona

The shape of the computed wave will usually more nearly approach the shape of the actual wave if its sharp corners are slightly rounded. Physically this is due to the resistance of the line and ground, particularly as influenced by skin effect.[7]

Table I

Data From	n^+	n^-
Predicted from 60-cycle corona	2.4 . . . . 3*.	3.6
Brune and Eaton (figure 8)	$2^1/_4$	4
Conwell and Fortescue (figure 9)	$2^1/_2$	—
Dykes (figure 3)	$2^1/_2$	4
Dykes (figure 6)	4	6
Skilling (figure 7)		5†

* Average of polarities.
† Polarity unknown.

Other Theories

So far as is known to the author, there has been no previous attempt to account *in detail* for the change in shape of traveling waves due to corona loss. Boehne[11] in 1931 suggested that the change in shape is due to a change of the capacitance of a line during corona (in this connection, see also a paper by Gardner[12]). Bewley[6] in 1933 discussed the change of shape of waves due to ground resistance, and offered a theory of traveling waves which involved 2 or more velocities of wave components. He proposed the extension of this discussion, which appears to give beautiful results at voltages below the corona-forming voltage, to explain distortion due to corona on the basis of a change of capacitance of that part of the line on which there is corona. There would be no sharp distinction between such a theory and the one that is used in this paper if it were possible to express the postulated change in capacitance as a function of the voltage and to include the loss of energy involved. But when loss of energy is omitted, and only distortionless wave components of different velocities are considered, the extremely large attenuation which is actually produced by corona does not appear.

The following comment should be made in this connection. Distortion due to corona becomes less as the voltage of a surge is diminished, and the wave tends to flatten out, with the voltage of its flattish top equal, generally speaking to the corona-forming voltage. This is illustrated by both waves of figure 8, at the 14-mile position. But many factors which are of negligible importance when the surge voltage is high make themselves felt when the surge voltage is low. Energy lost due to line resistance and ground resistance, and energy transferred inductively to nearby conductors, are overshadowed at high voltage by the great loss of energy due to corona. At lower voltage they have much to do with determining the shape of the wave. It can be seen, for instance, by reference to the original oscillograms of the paper by Brune and Eaton,[7] that the waves of figure 8 at the 14-mile position do not have a simple flat top, but appear, in detail, to have 2 rather distinct humps. It is interesting to consider this shape in the light of the theory of multivelocity components. But it will also be seen from Brune and Eaton's curves that this is a minor effect which does not appear while rapid attenuation by corona is taking place. In other words, the reduction of lightning voltage from a dangerous value to a safe value is the result of energy loss in corona.

Any of the various empirical formulas which have been proposed can only hope to be true for an imposed wave of some standard form. This is clearly true when one considers that the corona loss at any particular voltage depends not only on the value of that voltage but also on the rate of change of voltage at that point; and consequently the rate of decrease of the crest voltage of a traveling wave depends on the shape of the entire wave. It is perfectly certain that any successful formula for the distortion and attenuation of waves that are affected by corona must take into account the whole wave, and not just the maximum voltage at the wave's crest.

Conclusions

This paper is a derivation and discussion of a formula for the change of shape of a traveling wave that is distorted and attenuated by corona. The formula, equation 14 of the paper, is

$$t = F_0(e) + \frac{k}{ncv}\frac{(e - e_0)}{e}s + \frac{s}{v}$$

The first term of the right-hand member is the initial shape of the wave, and the second term is the change of shape due to corona. (The third term merely accounts for the lapse of time while the wave travels.)

All quantities in this formula, except n, can easily be predetermined. The factor k is found from the measured or computed corona loss of the line at normal frequency. Approximate values of n are 2.5 for positive waves and 4 for negative waves, but more data are needed to substantiate these values and to determine their range of application.

The derivation of the proposed law involves several approximations, but its agreement with experimental results over a wide variety of conditions is reassuring.

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Relaxation of Copper

With the present tendency to employ higher temperatures in various industries, more extensive investigation of the behavior of metals at elevated temperatures has become important. Under a grant received from the Engineering Foundation during the years 1935–36, work on this subject was done by John Boyd with the facilities offered by the research laboratories of the Westinghouse Electric & Manufacturing Company in co-operation with the University of Pittsburgh, and reported in the paper "Relaxation of Copper at Normal and at Elevated Temperatures," which was presented at the annual meeting of the American Society for Testing Materials at New York, N. Y., June 28–July 2, 1937. The problem was suggested by Doctor A. Nadai of the Westinghouse laboratories.

The phenomenon of the decrease of stress at constant length, such as occurs in bolts, has been called relaxation. Some investigation of this phenomenon has been made, but few of the methods used have attempted to produce pure relaxation conditions. The tests described in this paper were made with an apparatus designed to eliminate the principal difficulties of former methods. Special attention was directed toward fulfilling the conditions of pure relaxation, that is, measuring the decrease in stress while the length of the test piece is carefully kept constant. Copper was chosen as a test material because of its importance in electrical machinery as well as its relative simplicity, and was used in the form of wire 0.204 inch in diameter.

A complete correlation has not as yet been made between data for relaxation and creep, which is the increase in length with time for material at constant stress. All experimental evidence seems to show that the creep rates found in relaxation tests are greater than those obtained from creep tests under what were assumed to be similar conditions. As a result, the magnitude of the decrease in stress in relaxation is larger than at first would be expected from considerations based upon creep rates observed in tests made with constant stress. A brief summary of the results is as follows:

1. For practical purposes, the relaxation of copper at room temperature and probably up to 200 degrees centigrade may be represented by an expression of the form:

$$\sigma = \sigma_i\,[1 - A \log (1 + Bt)]$$

where σ is the stress at any time t, σ_i is the initial stress, and A and B are constants.

2. A marked increase in relaxation takes place when the temperature is raised above about 80 degrees centigrade. At 200 degrees centigrade the stress is estimated to fall to about 20–25 per cent of its initial value in a service time of 20 years.

3. Recovery effects tend to decrease the creep rate found in the early part of a relaxation test.

4. The dissimilarity between the speed laws for decreasing and for increasing stress gives rise to rather large amounts of relaxation.

Further creep and relaxation tests are at present under way and may be expected to add to knowledge of this subject.

The Saturated Synchronous Machine

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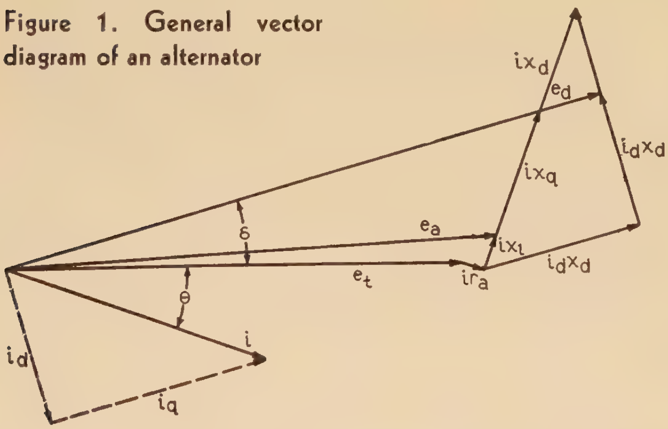
WHILE the unsaturated synchronous machine is in general well understood, the effects of saturation upon its performance are still subject to discussion. Knowledge on the influence of saturation is important because of power-angle relations, steady-state stability limits, and excitation requirements. The problem of saturation may be approached in several ways. One method[1] is to determine empirical factors which modify characteristics of the unsaturated machine, the saturation factors being single average values for a group of machines. A second way[2] leads to the introduction of equivalent reactances which allow calculation of the effects of saturation on small load changes about an initial operating point. Third, there is the derivation[3] of saturated synchronous reactances to be used in the investigation of power-angle curves and maximum power.

It is the purpose of this paper to present the physical concepts underlying the highly saturated synchronous machine operating under steady load, and to show how the theory developed for such a machine is in agreement with test results. With terminal voltage, current, and power factor known, the torque-angle and excitation may be determined accurately.

Figure 1. General vector diagram of an alternator



The analysis here proposed is general in that it applies to both salient-pole and cylindrical-rotor machines. It is based on Blondel's[4] 2-reaction theory of synchronous machines, and is a modification of the vector diagram given by Doherty and Nickle[5] in their extension of Blondel's work. The diagram for the unsaturated machine assumes constant values for armature resistance and the several reactances, and linear relations existing throughout the machine. Assuming no saturation in the armature or cross-field paths, figure 27 of the paper by Doherty and Nickle shows an additional field excitation along the pole axis to take into account saturation in the pole body. Under these assumptions, the torque-angle is not affected by saturation. Under conditions of saturation, and certainly for high saturation, all of the machine reactances are decreased in magnitude. The cross-field path, by way of the pole tips, and the armature teeth, will saturate as well as the pole body. Torque-angle therefore is appreciably affected as well as is the excitation requirement.

Machine Constants

The machine constants which must be considered in any steady-state analysis of the synchronous machine are armature resistance, armature leakage reactance, and the direct and quadrature synchronous reactances. The effective armature resistance may be determined by methods previously described.[6] Tests on armature leakage reactance[7] have shown that it varies somewhat with saturation, being a function of the density in the armature teeth which in turn depends upon the air-gap flux. The variation, however, is relatively small, and without introducing appreciable error this quantity may be taken as a function of terminal voltage.

The synchronous reactances are a measure of the flux which the armature magnetomotive force produces in its magnetic circuit. In the case of the direct synchronous reactance the magnetic circuit consists of the armature iron, the air-gaps, and the rotor poles and spider. For the quadrature synchronous reactance the magnetic circuit consists of the armature iron, the air-gaps, the pole tips, and the interpolar region. With increasing flux through these circuits, the synchronous reactances decrease. While x_q is a function of the voltage behind leakage reactance, or the total air-gap flux, x_d depends also upon the field leakage to the extent that this flux increases saturation in the pole body.

The synchronous reactances are defined in terms of armature quantities, i.e., x_d, the direct synchronous reactance, is the ratio of the fundamental component of the reactive armature voltage, due to the fundamental direct-axis component of armature current, to this component of current under steady state conditions and at rated frequency. The quadrature synchronous reactance, x_q, is defined similarly. Slip tests,[9] which are used to obtain both x_d and x_q, also may be used to determine the saturated values of these quantities. Subtracting vectorially the armature resistance and leakage reactance voltages from the terminal voltage, the synchronous reactances may be

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1. For all numbered references, see list at end of paper.

plotted as functions of the air-gap voltage. The air-gap voltage, e_a, may be expressed[8] as

$$e_a = e_t[\sqrt{1 - (r_a/x)^2} - x_l/x]$$

where $x = x_d$ or x_q, as desired. e_t is the terminal voltage and r_a the armature resistance. The treatment presented in this paper makes use of the unsaturated direct and quadrature synchronous reactances, and the saturated quadrature synchronous reactance.

The Vector Diagram

The steady-state performance of the unsaturated synchronous machine may be represented by a vector diagram.

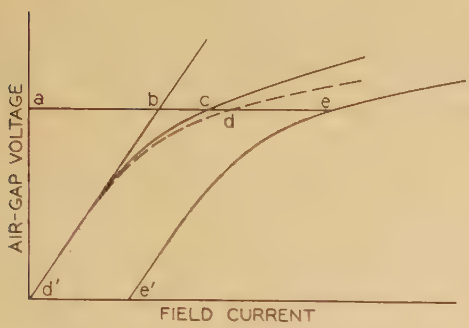

Figure 3. Relation between zero-power-factor curve and field current required for pole leakage under saturation

Figure 1 shows such a diagram for an alternator operating at a lagging power factor. The purpose of the diagram is ultimately to give the torque-angle and excitation requirement of the machine under load. This paper follows the per-unit notation, and the nomenclature is given in the following tabulation:

e_t = machine terminal voltage
i = armature current
θ = power factor angle
r_a = effective armature resistance
x_l = armature leakage reactance
e_a = air-gap voltage (voltage behind leakage reactance)
x_d = direct-axis synchronous reactance

Table I. Comparison Between Calculated and Test Values of Torque-Angle and Excitation for the Saturated Salient-Pole Synchronous Machine

Three phase, 6 pole, 40 horsepower, 1,200 rpm, 440 volts, 44.5 amperes

e_t (Volts)	i_{avg} (Amperes)	W_1 (Kilo-watts)	W_2 (Kilo-watts)	Angle (Degrees) Calculated	Angle (Degrees) Test	I_f (Amperes) Calculated	I_f (Amperes) Test
Motor, 0.8 power factor leading							
535	0	0	0	0	0	7.05	7.05
535	6.7	3.56	1.42	2.7	2.8	7.61	7.51
535	11.45	6.08	2.40	4.6	4.8	8.05	7.97
535	15.15	8.05	3.19	6.0	6.0	8.37	8.30
535	21.0	11.17	4.47	8.1	8.0	8.98	8.88
535	25.8	13.72	5.52	9.8	10.0	9.48	9.40
535	30.0	15.96	6.39	11.0	11.0	9.99	9.92
535	37.3	19.82	7.76	13.3	13.2	10.90	10.70
Motor, unity power factor							
535	0	0	0	0	0	7.05	7.05
535	8.25	3.82	3.82	4.3	4.2	6.97	7.00
535	15.95	7.40	7.40	8.1	8.1	7.01	7.04
535	24.5	11.36	11.36	12.5	12.3	7.11	7.20
535	31.9	14.80	14.80	16.1	16.0	7.29	7.39
535	39.6	18.35	18.35	19.8	19.8	7.58	7.70
535	46.8	21.70	21.70	23.1	23.1	7.84	8.05
Motor, 0.8 power factor lagging							
535	0	0	0	0	0	7.05	7.05
535	7.75	1.61	4.11	3.0	3.0	6.34	6.38
535	15.5	3.21	8.22	6.4	6.3	5.71	5.76
535	22.85	4.83	12.15	10.0	10.2	5.18	5.20
535	28.05	5.95	14.90	12.7	12.8	4.86	4.93
535	33.95	7.14	18.04	16.0	16.0	4.55	4.62
535	39.1	8.06	20.74	18.8	18.7	4.29	4.40
535	44.5	9.54	23.66	22.1	22.0	4.23	4.36

x_q = quadrature-axis synchronous reactance
x_{ad} = direct-axis reactance of armature reaction
δ = torque-angle
i_d = direct-axis component of armature current
i_q = quadrature-axis component of armature current
e_d = excitation voltage giving field current for no saturation
I_f = field current

The vector diagram of figure 1 is general, and is essentially that shown by Doherty and Nickle in "Synchronous Machines–I."[5] From it, for the unsaturated machine, may be obtained directly the displacement

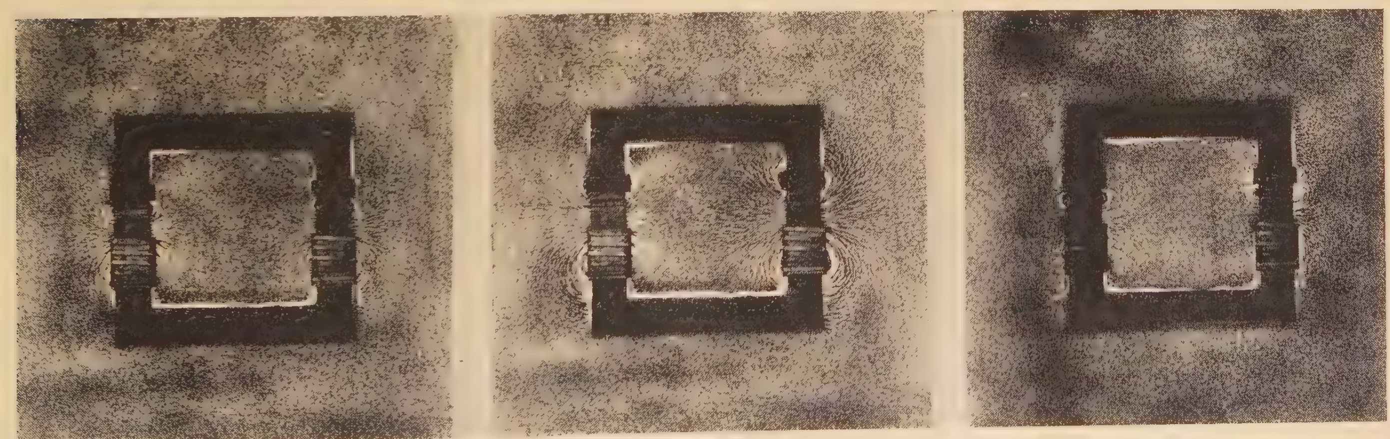

Figure 2. Iron-filing pictures to illustrate effects of armature magnetomotive force on field leakage flux. Armature windings above, field windings below

Left—No-load representation. Armature $NI = 0$, field $NI = 150$. Center—Demagnetization. Armature $NI = 150$, field $NI = 300$. Right—Magnetization. Armature $NI = 75$, field $NI = 75$

angle, δ, and the field current, I_f, corresponding to the excitation voltage, e_d. It is assumed that the reader is familiar with the method.

With saturation, however, the torque angle is decreased, and the required field current is increased. These statements hold regardless of motor or generator action, or of power factor. The angle obtained by way of the unsaturated machine constants must be corrected, and the proposal made in this paper is to determine that angle directly by using the saturated value of x_q to locate the true direct axis. The angle is thus given immediately without subtracting a correction angle. The closeness with which test results agree with this method of determining torque angle is shown in tables I–IV.

In appendix *D* of "Synchronous Machines–I and II," Doherty and Nickle outline a manner of obtaining the increase in excitation to care for saturation. Figure 27 of that paper contains the fundamental ideas involved. The projection on the direct axis of the voltage behind leakage reactance is carried to the saturation curve, the field current to be added being that measured by the horizontal separation between the air-gap line and the no-load saturation curve. This added field current, however, is not sufficient for the saturated machine with demagnetizing armature current. Depending upon the degree of saturation and the armature current, it may be far less than is required. On the other hand, the machine with magnetizing armature reaction is overcompensated in field current.

Table II. Comparison Between Calculated and Test Values of Torque-Angle and Excitation for the Saturated Salient-Pole Synchronous Machine

Three phase, 6 pole, 7.5 kva, 1,200 rpm, 220 volts, 19.7 amperes

e_t (Volts)	i_{avg} (Amperes)	W_1 (Kilowatts)	W_2 (Kilowatts)	Angle (Degrees) Calculated	Angle (Degrees) Test	I_f (Amperes) Calculated	I_f (Amperes) Test
Motor, unity power factor							
540	0	0	0	0	0	10.60	10.60
540	5.3	2.42	2.42	2.8	2.7	10.35	10.32
540	10.5	4.92	4.92	5.4	5.4	10.20	10.22
540	15.6	7.37	7.37	8.1	7.8	10.17	10.20
540	20.3	9.55	9.55	10.3	10.2	10.20	10.20
Motor, 0.8 power factor lagging							
540	0	0	0	0	0	10.60	10.60
540	6.2	1.37	3.19	2.3	2.5	9.70	9.74
540	11.3	2.47	5.93	4.4	4.8	9.00	9.03
540	16.35	3.46	8.63	6.5	6.7	8.37	8.42
540	21.6	4.65	11.42	8.9	8.9	7.71	7.72

Table III. Comparison Between Calculated and Test Values of Torque-Angle and Excitation for the Saturated Cylindrical-Rotor Synchronous Machine

Three phase, 6 pole, 7.5 kva, 1,200 rpm, 220 volts, 19.7 amperes

e_t (Volts)	i_{avg} (Amperes)	W_1 (Kilowatts)	W_2 (Kilowatts)	Angle (Degrees) Calculated	Angle (Degrees) Test	I_f (Amperes) Calculated	I_f (Amperes) test
Motor, unity power factor							
450	0	0	0	0	0	67.0	67.0
450	5.5	2.04	2.04	17.5	17	67.1	67.2
450	9.95	3.78	3.78	30.9	30.5	69.8	71.5
450	14.9	5.76	5.76	43.0	43	80.2	82.0
450	20.5	7.92	7.92	53.2	53	95.8	97.0

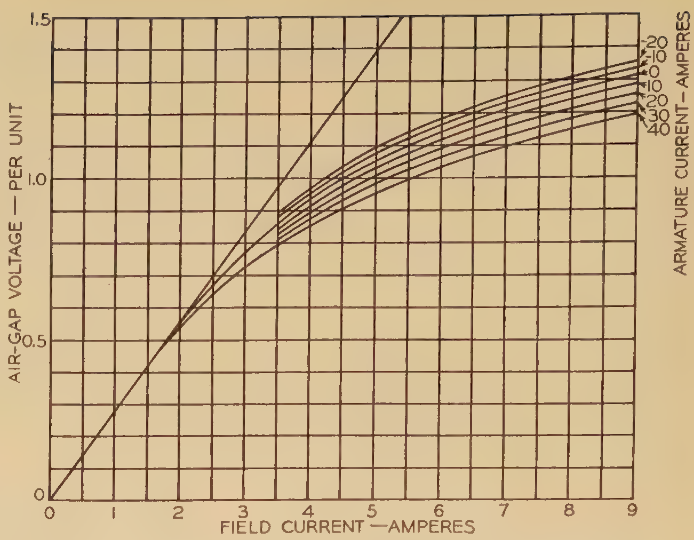

Figure 4. Zero-power-factor curves for determination of field current required for saturation

Part of the field magnetomotive force which must be added to care for saturation is that required to force the flux through the entire saturated circuit, and is represented by the distance between the air-gap line and the no-load saturation curve. This component takes care of normal field leakage at this flux density. In addition a second component of magnetomotive force is required to force an increased leakage flux through the saturated path at the base of the pole due to the demagnetizing effect of the i_d component of armature current. The second portion of magnetomotive force may be represented by an additional number of ampere turns indicated on the saturation curve by the distance between the no-load curve and what may be called the field leakage curves.

Field Leakage

The magnetomotive forces of the field and armature windings act on the main magnetic circuit of the machine to produce the resultant flux. These magnetomotive forces may wholly oppose each other, as in the case of the zero-power-factor-lagging generator (zero-power-factor-leading motor), or they may wholly assist each other. Between these 2 extremes the armature current will have one component which is directly magnetizing or demagnetizing, and a second component which acts on the cross-field magnetic circuit. The first of these supplies the direct component of armature magnetomotive force, and the second is synonomous with the quadrature component of armature magnetomotive force. The strength and relative direction of the components depend, of course, upon both load current and power factor.

Under no load, and below saturation, equal increments of field current produce equal increments of total flux through the field coils. By far the greater part of the flux follows the main magnetic circuit and is mutual to both field and armature windings. The other part encloses

the field winding alone and is known as field leakage flux, most of it being located near the base of the pole. Both parts increase in the same proportion up to the point of saturation. With saturation, successive equal increments of field current produce diminishing increments of total flux, the increments of the mutal or air-gap flux being less in proportion to the increments of field leakage flux up to a certain point of saturation which usually is beyond the working range of any machine. The reason for this phenomenon is that the main flux follows a path consisting mostly of iron, while the path of the leakage flux has a far greater ratio of air to iron. At extremely high saturation, when the reluctance of the iron in the main path is very

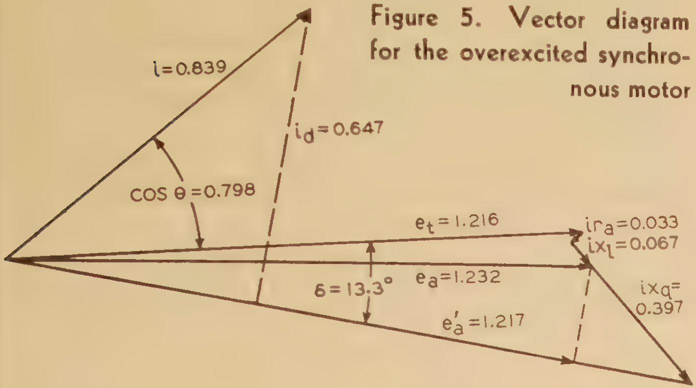

Figure 5. Vector diagram for the overexcited synchronous motor

great, the increments of air-gap and leakage fluxes approach a constant ratio again, although not the same ratio as for no saturation.

With no saturation, and for a given air-gap flux, any demagnetizing ampere turns of the armature must be met by an equal rise in field ampere turns. The field leakage obviously increases. Similarly, magnetizing armature current requires an equal decrease in field magnetomotive force with a corresponding reduction in field leakage flux. Although this leakage flux varies, it maintains the same linear relation with respect to total field magnetomotive force as exists at no load, no saturation.

Under saturation, and at no load, there exists a given field current to provide a desired air-gap flux. If with the application of demagnetizing armature ampere turns the field ampere turns are increased by an equal amount, there will be an increase in pole saturation due to the increase in field leakage flux. This increased saturation decreases the air-gap flux, and to maintain the desired air-gap flux the field ampere turns must be increased by an additional amount to overcome the effects of the greater pole saturation. Conversely, magnetizing armature ampere turns will require a decrease in field ampere turns greater than the corresponding change in armature magnetomotive force.

The iron-filing pictures of figure 2 are given as an aid in visualizing field leakage, the circuit representing the elements of the sychronous machine. Figure 2*a* indicates conditions of no load. Figures 2*b* and 2*c* show the effects of armature magnetomotive force on field leakage for the 2 cases of demagnetizing and magnetizing armature ampere turns. The same air-gap ampere turns exist in all cases.

Field Leakage Curves

The full lines $d'c$ and $e'e$ of figure 3 show, respectively, the no-load and the full-load zero-power-factor overexcited saturation curves of a synchronous machine. Whereas the horizontal separation at the zero ordinate in the usual manner of treatment is that value of field current which would produce a voltage on the air-gap line equal to ix_d, in figure 3 the separation corresponds to ix_{ad}. Similar curves may be obtained for any value of magnetizing or demagnetizing armature current.

The dotted curve $d'd$ of figure 3 is the zero-power-factor curve moved to the left by that amount of field current corresponding to the voltage of armature reaction for unsaturated conditions. The distance *ae* represents the total field current required to produce, with full-load demagnetizing ampere turns on the armature, the air-gap voltage indicated. This total field current may be thought to consist of several components. The first is that which produces the magnetomotive force to overcome the demagnetizing effect of armature reaction, and is given by *de*. The second component, *ab*, is the field current required to send the main flux across the air gap. The third component, *bc*, is that necessary to force the mutual flux through the iron of the magnetic circuit under conditions of no-load saturation. Lastly, there is the added field current, *cd*, to care for the increased saturation caused by the increased field-leakage flux which in turn is caused by the demagnetizing armature current. This fourth component of field current is a function not only of air-gap voltage but also of armature demagnetizing magnetomotive force.

Figure 4 shows a family of field leakage curves plotted in the manner described, where the initial curves have been moved over by the amount of the respective field currents corresponding to the armature reactance voltages. The data for the curves were obtained by test on the 40-horsepower synchronous motor (described later under "Test Results") employing a single-turn full-pitch test coil so placed on the armature surface that it enclosed the main air-gap flux. Because the vector diagram for the

Table IV. Comparison Between Calculated and Test Values of Torque-Angle and Excitation for the Saturated Salient-Pole Synchronous Machine

Three phase, 6 pole, 15 kva, 1,200 rpm, 220 volts, 39.4 amperes

e_t (Volts)	i_{avg} (Amperes)	W_1 (Kilowatts)	W_2 (Kilowatts)	Angle (Degrees) Calculated	Angle (Degrees) Test	I_f (Amperes) Calculated	I_f (Amperes) Test
Motor, unity power factor							
277	0	0	0	0	0	11.88	12.10
277	10.2	2.45	2.45	4.4	4.5	11.83	12.02
277	19.8	4.75	4.75	8.8	8.8	12.02	12.04
277	29.4	7.06	7.06	13.2	13.1	12.64	12.60
277	39.06	9.37	9.37	17.7	17.9	13.42	13.45
277	48.4	11.62	11.62	21.9	22.0	14.37	14.30

synchronous machine is based on fundamental voltages, harmonics in the air-gap voltage were eliminated by using a wave analyzer, thus giving the values of fundamental voltage directly.

For an overexcited machine at zero power factor, the armature current is wholly demagnetizing and is represented in the vector diagram by a positive i_d. Conversely, for an underexcited machine at zero power factor the armature current is magnetizing and is designated by a negative i_d. The field leakage curves indicate these relations, the parameter being amperes armature current. The curves are entered with the direct axis component of the air-gap voltage. The horizontal distance between the no-load saturation curve and the interpolated curve for the direct axis component of armature current, also found from the vector diagram, is the field current required to supply the increased field leakage flux caused by that component of armature current.

Application

The application of the foregoing theory is illustrated by 2 examples. The first is that for the 40-horsepower overexcited synchronous motor operating at 535 volts with a line current of 37.3 amperes at 0.789 power factor. Figure 5 is the vector diagram for this case with all corresponding quantities given in per-unit terms. The torque-angle of the machine is found immediately upon location of the direct axis and is 13.3 electrical degrees, agreeing with the angle of 13.2 degrees obtained by test.

The field current is calculated on the assumption of no saturation, the method following that discussed in conjunction with figure 1. To this value of field current there is added a correction for saturation. Following the method of Doherty and Nickle, the direct-axis component of the voltage behind leakage reactance is carried to the field leakage curves, figure 4. The field current correction is given by the distance between the air-gap line and the interpolated field leakage curve corresponding to the value of i_d in amperes.

The second example, shown by figure 6 is that of the underexcited synchronous motor operating at 535 volts with a line current of 44.5 amperes at a power factor of 0.805. The procedure in determining the torque-angle and excitation is the same as for the first example with the exception that i_d is now negative, indicating magnetizing action of the armature current. It is to be observed that the diagrams of figures 5 and 6 are for purposes of correction, and do not completely represent the unsaturated machine.

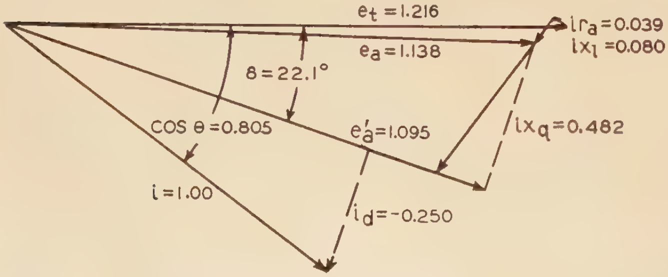

Figure 6. Vector diagram for the underexcited synchronous motor

Test Results

Tables I–IV show the comparison between calculation and test of torque-angle and excitation for synchronous machines operating at high voltages under steady load. The data of table I were taken on a salient-pole general-purpose synchronous motor rated 3 phase, 6 pole, 40 horsepower, 1,200 rpm, 440 volts, 44.5 amperes. Tests were taken on the machine, both as a motor and as a generator, over a range of voltages extending from below saturation to 535 volts. All calculations gave the same close agreement with test as shown in the table, but for purposes of comparison only the results of 3 general conditions of load are presented. The curves of machine constants used in these calculations are given by figures 7–9. Motor operation at 535 volts was chosen for presentation because of the high degree of saturation introduced, coupled with the fact that the motor still could carry approximately rated current before reaching the limit on instruments or commutation of the d-c machine connected to it.

Tables II and III show data on a 3-phase 6-pole 7.5-kva 1,200-rpm 220-volt 19.7-ampere alternator designed for operation as a salient-pole generator or as a wound-rotor induction motor by interchanging rotors. Table II gives results for operation of the machine as a salient-pole motor. Table III shows data for operation of the machine as a cylindrical-rotor synchronous motor, direct current having been supplied the wound rotor. Due to the fact that saturation was extremely small at rated voltage, tests were carried out at the relatively very high voltage shown.

Figure 7. Effective armature resistance of a 40-horsepower 1,200-rpm 440-volt synchronous motor

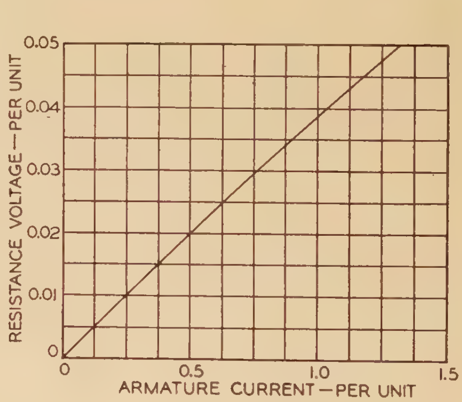

Table IV gives similar results on a 3-phase 6-pole 15-kva 1,200-rpm 220-volt 39.4-ampere generator. Due to inherent voltage unbalance within this machine, the field current did not check the saturation curve when the machine was connected to an infinite bus with no power exchange. This also accounts for the small discrepancies between calculated and tested field currents at the lower loads.

Zero readings were obtained by adjusting the field currents on both machines so as to give no deflection on the

wattmeters. All constant losses therefore were supplied by the d-c machine. Measurements were taken at those times when the power supply gave balanced voltages because it was found that an unbalance, although very small, introduced errors. Adjustments of the wattmeter readings for desired power factors were occasionally a trifle difficult to make under pump-back operation of the set. Limits on instruments, field heating, and commutation of the d-c machine prevented loading the synchronous motor as highly as was desired.

Summary

The theoretical discussion given in the paper offers a general method of treating the highly saturated synchro-

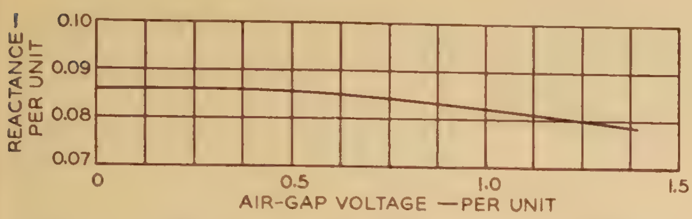

Figure 8. Armature leakage reactance of a 40-horsepower 1,200-rpm 440-volt synchronous motor

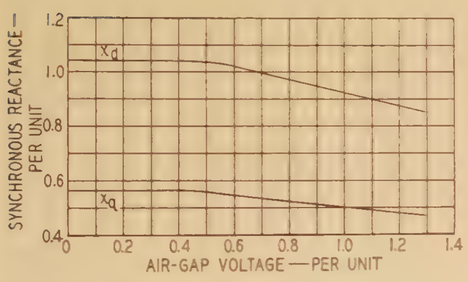

Figure 9. Variation of synchronous reactances with saturation for a 40-horsepower 1,200-rpm 440-volt synchronous motor

nous machine operating under steady load. To as great an extent as possible the mode of attack employs the accepted form of the vector diagram based on Blondel's 2-reaction theory. Torque-angle is obtained by using the saturated quadrature synchronous reactance rather than the unsaturated reactance. Saturation in the interpolar axis affects the displacement angle of the machine, the angle decreasing with saturation, thus leading to a stiffer machine. For accuracy, the effective armature resistance may not be neglected, at least for smaller machines.

While direct axis saturation requires less field current to overcome direct armature reaction, this decrease is more than offset by the required increase in field current to care for increased field leakage flux caused by this direct armature magnetomotive force. The total field current may be thought to consist of several components; one to force the mutual flux across the gap, a second to overcome armature reaction, a third to care for no-load saturation, and a fourth to account for an increase or decrease in saturation due to a change in pole leakage when current is present in the armature. In a manner, the first 2 components are included in the calculation from the vector diagram for the unsaturated machine. The last 2 are obtained from field leakage curves.

The paper is offered as a theoretical analysis on the effects of saturation, and as such should lead to a better understanding on the performance of the synchronous machine. In addition, it should aid in the proper evaluation of empirical methods, and in furthering studies on the saturated machine operating under transient conditions. It is felt that the good agreement between calculation and test results, as shown in the tables, greatly substantiates the theory given in the paper.

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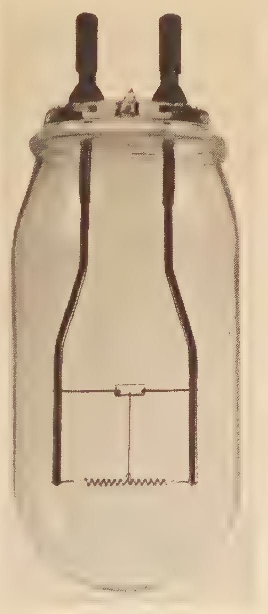
New Bipost-Base Street-Series Lamp

A new type of street-series lamp has been designed especially for use in "high visibility" lighting equipment. The 4,000-lumen lamp, which is $6^1/_2$ inches in length and which is designed to burn base up, is equipped with a medium bipost base, a relatively small tubular-shaped bulb of clear hard glass, and a horizontal bar filament about one inch long. Application of the bipost method of construction results in the following advantages: reduction of inaccuracies in filament positioning, permanency of lamp and reflector adjustment, a major reduction in size, a rugged straight-sided bulb which is immune to bulb breakage from sudden temperature changes and which is less likely to collect dirt than pear-shaped lamps, and a simplified filament assembly which eliminates several old steps formerly required in lamp making, with economy for both user and maker.



Discussions

Of AIEE Papers—as Recommended for Publication by Technical Committees

On THIS and the following 45 pages appear discussions submitted for publication, and approved by the technical committees, on papers presented at the sessions on communication, electric welding, electronics, instruments and measurements, power distribution, selected subjects, and synchronous machinery at the 1937 AIEE winter convention, New York, N. Y., January 25–29. Authors' closures, where they have been submitted, will be found at the end of the discussion on their respective papers. Other discussion of winter convention papers will be published as it is made available.

Members anywhere are encouraged to submit written discussion of any paper published in Electrical Engineering, which discussion will be reviewed by the proper technical committee and considered for possible publication in a subsequent issue. Discussions of papers scheduled for presentation at any AIEE meeting or convention will be closed 2 weeks after presentation. Discussions should be (1) concise; (2) restricted to the subject of the paper or papers under consideration; and (3) typewritten and submitted in triplicate to C. S. Rich, secretary, technical program committee, AIEE headquarters 33 West 39th Street, New York, N. Y.

The Resistance Welding Circuit

Discussion and author's closure of a paper by C. L. Pfeiffer published in the August 1936 issue, pages 868–73, and presented for oral discussion at the electric welding session of the winter convention, New York, N. Y., January 28, 1937.

H. C. Cogan (nonmember; National Electric Welding Machines Company, Bay City, Mich.): Mr. Pfeiffer's paper "The Resistance Welding Circuit" is very timely. Since the advent of positive cycle control apparatus for resistance welding equipment, and further, since the welding machines themselves have been improved considerably, materials are now being welded by the resistance method that demand close calculation as to their power-demand and welding-circuit conditions.

The welding-machine manufacturers can, through accepted and now standard calculations determine the total impedance of a welding machine circuit (electrodes to transformer) and thereby design a transformer and circuit to deliver a specified current at the weld.

It has not been very easy, however, to calculate the desired current at the weld and thereby specify the fundamental requisite as a starting point for machine and transformer design.

Mr. Pfeiffer's paper is very interesting inasmuch as it shows original methods and a very clear analysis of the possible determination of the voltage-drop and current characteristics at various points in the weld area proper. With the development of methods as outlined in this paper the capacity of resistance welding equipment may be known in time by the maximum current (secondary amperes) that can be delivered at the welding electrodes at a predetermined primary supply, all of which can be definitely put on the name plate of the welding machine, and this alone will be a great step forward in a mutual understanding among the user of the welding machine, the manufacturer of the welding machine, and the power company supplying the power, which supersedes the antiquated and useless kilovolt-ampere rating of resistance welders.

C. E. Heitman (Edward G. Budd Manufacturing Co., Philadelphia, Pa.): To those of us vitally concerned with resistance welding and its applications, it is gratifying to note an increasing amount of published information concerning this subject. Mr. Pfeiffer's present paper is noteworthy in that it emphasizes the effect which the electric circuit has upon the successful operation of any resistance welding application. This phase of the problem has been more or less neglected in the past, perhaps because the earlier types of machines did not require such a thorough analysis of the electric circuit as more elaborate machines of today.

The author's discussion of this subject is indeed interesting, although the examples cited apply to a type of welder with which I am not very familiar. All of the spot welding applications with which I have been concerned demand machines having much higher secondary or lead impedances than shown in the vector diagrams of figure 3, due to the physical characteristics of the product being welded. For this reason, I feel that the ratios obtained from these vector diagrams may be misleading if applied to the welding machines used in the average sheet-metal shop.

On various portable spot-welding jobs, wherein the welding electrodes are connected to the transformer by means of cables 5 or 6 feet in length, my experience has been that the voltage drop in these cables alone is approximately 85 per cent of the open-circuit secondary voltage of the transformer, and over 90 per cent of the secondary load voltage. In some cases these figures increase to 90 per cent and 95 per cent respectively. In such cases, little or no difference is made upon the amount of secondary current, whether there is ferrous metal between the electrodes or whether the electrodes are brought together with no metal between them. In the case of the upright stationary machine, the impedance of the leads may be a smaller percentage of the total secondary impedance, depending upon the length and spacings of these leads. In any event, I have found that this lead impedance is practically all reactance, so that this voltage drop must be added at right angles to the almost purely resistance voltage across the weld. For this reason, the impedance of the weld does not add materially to the total circuit impedance. In all such cases the voltage drop across the weld is considerably less than the voltage drop in the secondary leads, even when welding relatively thick sheets of ferrous materials. In cases where the coupling between electrodes and transformer is very close and where the spacing between these leads is small, the values given by the author would no doubt apply, but such machines have comparatively little utility in large sheet metal plants.

I mention these welding conditions as being typical of those with which I have dealt, and which I believe are typical of other manufacturing plants, in the hope that it may shed some additional light upon the problem, and perhaps stimulate further discussion. The field of resistance welding is very broad, and impossible to thoroughly cover in any one discussion.

I wish to express my thanks and appreciation to the author for a most interesting and enlightening discussion of this subject.

J. W. Dawson (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): The author is most sincerely concurred with in his hope that this elementary paper will stimulate a more thorough investigation of the resistance welding circuit which is so well known and yet so imperfectly understood.

Phenomena occurring in the weld area are very much of transient nature. During the welding period, the electrical, thermal, and metallurgical conditions and even electrode pressure undergo very rapid changes, particularly in so-called "short time" welding. This fact adds to the other practical difficulties in thoroughly investigating this area.

An important part of future study of the resistance welding circuit will undoubtedly concern itself with the adjoining surface layers of the parts being welded, and the transmutation of their contact resistance into the resistance of highly heated metal layers during the weld. The author's discussion of surface film break-down is of interest in this connection.

The author presents data in tabular form showing the voltage drop in various parts of the resistance welding circuit. It is under-

stood that instrument measurements were necessarily made with relatively long welding periods. Mention is made, however, of oscillographic measurements of these quantities and it would be of interest to learn whether the oscillograph showed appreciable changes in weld area voltages during welding.

The author's use of work-body resistance as a criteria in roughly calculating conditions in the weld area, seems to the writer a rather inaccurate basis of approach to this problem. Although less convenient, the all important contact surface resistances are given too little attention. Likewise, Jean's formula $r/4a$ would not seem to apply here. The chief justification for considering the problem in the light of this formula should lie in the fact that resistance is assumed a function of the number of contacting surfaces. Even on the basis of metal-body resistance, this formula should not give correct results since the sheets are of small dimension in the direction of current flow although, as stated by the author, of very large cross section.

Referrring to the 2 vector diagrams, figure 3, it is not clear to the writer how the vector quantity E_t denoting transformer voltage drop has been determined from the measurements given.

The writer cannot entirely agree with the author in that definite energy input to the weld is always the ideal basis for terminating the weld, although in "slow" welding, it would seem a step in the right direction. First of all, the rate of applying energy to the weld area is extremely important, particularly in "short time" welding, one factor being the flow of thermal energy away from the weld through body of the work. Considering the extreme case, a proper total quantity of energy might be applied to the weld but at such extremely low rate as to result in barely warming the weld surfaces. Secondly, and again particularly for the "short time" welding, it is very difficult to terminate the weld excepting at the end of $^1/_2$ cycle of current. For these reasons, accurate control of all factors would seem the best practice for "short time" welding, which is being much used at present.

H. A. Woofter (nonmember; The Federal Machine and Welder Company, Warren, Ohio): Mr. Pfeiffer's excellent paper on resistance welder circuits is one of the best that has been written to date. A few notations and elaborations might be helpful to the reader.

Referring to figures 4 and 5 the layman might take it for granted that because practically any number of projection welds can be made instantaneously from a single circuit as shown in figure 5, that it would immediately follow that practically any number of spot welds could be made instantaneously from a single circuit as shown in figure 4. It is an outstanding fact, however, that only one good spot weld can be made at one time from one circuit with one set of leads. The reason for this is as follows: A spot weld is virtually a short circuit of the secondary of the transformer. Now, when 2 or more points are used, or attempted to be used, the power will not break through all of the points at the same time. One spot will break through under one point first. This as stated above establishes a dead short circuit which knocks down the secondary voltage of the circuit to such an extent that the other points do not have sufficient voltage to make a good spot weld. This, however, can be corrected by bringing out a separate set of leads to each electrode point. It can also be further improved by having individual pressure applied to each individual point, such as a pressure spring, small hydraulic cylinder, air cylinder, or any of the well-known pressure devices.

Referring to figures 6 and 7, especially the latter, when attempting heavy work, requiring large amounts of power, the 3 transformers shown can sometimes be connected to the 3 phases of the power circuit, thus balancing the load on the power line. Under such conditions, however, it is necessary to insulate the 3 heads on one or both sides of the transformer to eliminate the leakage between phases, which on a 3-phase circuit is the square root of 3, which amounts to 1.73 times as much voltage between the phases as there is across the points of the welder.

While perhaps 99.99 per cent of resistance welding is done single phase there are some cases of projection welding, mash welding, wire-mat welding, etc., where the projections or intersections can be grouped into clusters of 3 or multiples thereof, and each cluster welded on a separate phase. This is sometimes done by connecting one side of the transformer to a single lower table with the 3 phases insulated above. At other times it is necessary to insulate the phases on both upper and lower tables.

L. H. Frost (nonmember; The Electric Controller & Mfg. Co., Cleveland, Ohio): Mr. Pfeiffer's paper indicates that the electrical circuit involved in a resistance-welding machine is not complicated and that the coordination of 3 principal factors; namely, current, electrode pressure, and time of current application, is essential to proper welding. This is true as a general statement, but it is not generally realized what effect changing values of these factors has upon the total result.

The current which will flow through the welding circuit depends upon conditions as outlined by Mr. Pfeiffer, but the current which is important from the angle of welding is the current which actually flows through the work pieces. Within reasonable limits, this current will be constant for given physical dimensions and electrical characteristics of the welding machine but may vary somewhat due to change of the effective resistance between the work pieces, and the work and the electrodes. In order to show clearly how these factors affect each other, and in general, the amount of heat required to make a weld, refer to figure 1, in which electrodes $E1$ and $E2$ are shown as being of conventional design. $S1$ and $S2$ are the 2 work pieces, in this case indicated as sheets. Between the work pieces and the electrodes are 2 contacting surfaces which have been designated as number 1 and number 3, respectively, and between the 2 pieces there are 2 other contacting surfaces which have been designated as number 2. The area involved in each of these conditions has been termed $A1$, $A3$, and $A2$, respectively.

It will be evident that the point of greatest resistance in this circuit is at the contacting surfaces themselves rather than through the various conducting portions of the circuit,

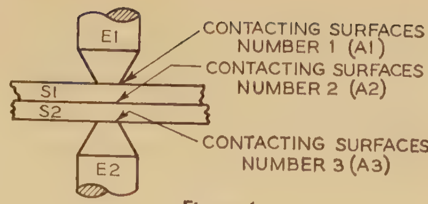


Figure 1

$$H_W = (H_D - H_L)t \tag{1}$$

but

$$H_D = I^2R \tag{2}$$

$$R = \frac{r_1}{P} + \frac{r_2}{P} + \frac{r_3}{P} \tag{3}$$

$$r_1 = \frac{C_1(\Omega_{E1} + \Omega_{S1})}{A_1P} \tag{4}$$

$$r_2 = \frac{C_2(\Omega_{S1} + \Omega_{S2})}{A_2P} \tag{5}$$

$$r_3 = \frac{C_3(\Omega_{S2} + \Omega_{E2})}{A_3P} \tag{6}$$

$$R = \frac{1}{P}\left(\frac{C_1}{A_1}(\Omega_{E1} + \Omega_{S1}) + \frac{C_2}{A_2}(\Omega_{S1} + \Omega_{S2}) + \frac{C_3}{A_3}(\Omega_{S2} + \Omega_{E2})\right) \tag{7}$$

$$H_L = K_{E1}V_1 + K_{S1}(V_2 + V_3) + K_{S2}(V_4 + V_5) + K_{E2}V_6 \tag{8}$$

$$H_w = t\left[\frac{I^2}{P}\left(\frac{C_1}{A_1}(\Omega_{E1} + \Omega_{S1}) + \frac{C_2}{A_2}(\Omega_{S1} + \Omega_{S2}) + \frac{C_3}{A_3}(\Omega_{S2} + \Omega_{E2})\right) + K_{E1}V_1 + K_{S1} \times (V_2 + V_3) + K_{S2}(V_4 + V_5) + K_{E2}V_6\right] \tag{9}$$

where

H_w = heat required for weld
H_D = heat developed by current
H_L = heat lost by conduction
t = time
I = current
R = resistance
r_1, r_2, r_3 = effective resistance at contacting surfaces 1, 2, and 3
C_1, C_2, C_7 = constants for resistivity of contacting surfaces, 1, 2, and 3
Ω_{E1}, Ω_{S1} = resistivity
Ω_{S2}, Ω_{E2} = resistivity
P = pressure
K_{E1}, K_{E2} = thermal conductivity of electrodes 1 and 2
K_{S1}, K_{S2} = thermal conductivity of sheet 1 and 2
V_1 = volume and gradient of electrode 1
V_6 = volume and gradient of electrode 2
V_2 = volume and gradient of sheet 1 affected by area A_1 and electrode 1
V_3 = volume and gradient of sheet 1 affected by areas A_1 and A_2
V_4 = volume and gradient of sheet 2 affected by areas A_1 and A_2
V_5 = volume and gradient of sheet 2 affected by area A_2 and electrode 2

therefore, heat will be generated at contacting surfaces number 1, and number 3 and also at number 2. It is further evident that the resistance between contacting surfaces number 2 must be greater than between surfaces number 1 and number 2, if a weld is to occur between contacting surfaces number 2. This is a general statement, of course, for there may be a wide dissimiliarity between the fusion points of the electrode material and the work pieces. It is possible to allow the heat to be conducted through from the outside surfaces to the center, but in general, this does not provide a satisfactory welding condition.

Following through the discussion applying to figure 1, we find that the total heat required for welding is equal to the heat developed by the passage of the current minus the heat lost due to conduction into the work pieces and electrodes, times the time required for welding. The heat developed follows I^2R, as shown in equation 2. Since R is the unknown and the variable in which we are interested in analyzing, this may be expanded as shown in equation 7. It will be noted that pressure has been introduced into the equation and that the resistance varies inversely with the pressure. This point has been shown in many tests relating to current carrying capacity of contacting surfaces and voltage drop across contacting surfaces and is familiar to everyone.

The heat lost is given in equation 8. The constant designated by K is the thermal conductivity of the electrodes and work pieces expressed in standard units. The factors designated as V_1, V_2, etc., are a combination of the volume and gradients involved. It will be evident that the gradient will not be linear as in the case of a steady condition, but will be a curve. A mathematical expression of this gradient has not been used as this would unnecessarily complicate the final equation. It should be noted, however, that since heat is being absorbed into the work pieces and into the electrodes at the same time, if there is a high temperature at contacting surfaces number 1, number 2, and number 3, and a low temperature in the electrodes and work pieces, that this gradient cannot be a straight line. The mathematical expression is complicated because of this fact and also because the temperature is increasing throughout the initial portion of the timing period. Therefore, the terminal temperature at the contacting surfaces is variable and that combined with the heat absorbed into the conducting materials makes this a complicated expression.

The final expression for the heat required for a weld is given in equation 9. It will be evident from this equation that the most important single variable in this equation is the time of current application. This is more important even than the amount of current applied since it affects not only the heat developed for welding, but also the heat lost by conduction. It is, therefore, important that the time of welding be controlled. The next most important variable is the current which, as indicated above, is influenced by the resistance of the welding circuit for given physical and electrical characteristics of the welding machine. The third most important variable is the pressure which affects the current inversely. From the equation 9 it will be evident that the relationship between the 3 principle factors of current, electrode pressure, and time of current application, is definite and it is possible to place the proper value in general upon each of these variables. From this equation it is also evident that if the resistivity of the electrodes and the work pieces are the same that the 3 expressions for resistance will be equal and that the heat will be divided in 3 points in equal amounts which will prevent satisfactory welding. This indicates one limit to which electrodes and materials may be changed.

To express this in concrete terms, it would be impossible to obtain satisfactory welds when using steel electrodes for welding steel sheets or by using copper electrodes for welding pure-copper sheets. This, of course, is for electrodes of conventional design as shown. It is sometimes possible, by using a special design, to change the constants C_1, C_2, and C_3.

The constants C_1, C_2, and C_3 must be determined by actual test. Also the effect of the factors V_1, V_2, etc., may be determined by actual test although in this case a mathematical expression can be obtained. It will be obvious that for various oxides and coatings on the work pieces, different values of C_1, C_2, and C_3 will be required. This will affect the electrical characteristics required in the welding machine to some extent as shown by Mr. Pfeiffer on page 871, but in general the adjustments on the machine permit a reasonably wide range of control for these conditions.

One interesting fact shown by equation 9 is that due to the relationship of current, electrode pressure, and time of current application, it is often possible by increasing the pressure to cause a decrease in resistance which for the given current requires an increased time to make the proper weld. This means that in the case of certain materials where practice has indicated that welds can be obtained only in the shortest possible time, that it may often be possible to increase the pressure and for the same current obtain satisfactory welds in a somewhat longer time.

Mr. Pfeiffer's article is certainly of importance in stimulating activity in the art of resistance welding. In the last few years there has been considerable done to improve means of timing the welds, but there is still much research work to be done in determining what factors influence the welding operation in detail. This work can best be done by educational institutions and engineering foundations, and if Mr. Pfeiffer's article or this discussion can stimulate any such activity, the effort expended in preparing the paper and this discussion will be amply repaid.

J. H. Zimmerman (nonmember; The Linde Air Products Company, Newark, N. J.): This simple treatment of the resistance-welding circuit should be of much help to the nonelectrical engineer and to the practical man who does resistance welding. It is hoped that the paper will also serve to stimulate more publications on the same subject, particularly papers dealing more specifically with phenomenal changes in the immediate vicinity of the weld as has been suggested by the author.

For example, little is known of the fluctuations, in electrode pressures during the short time interval of welding. It has been estimated that as much as 60 per cent of the original pressure may be relieved by the surge of current through the secondary. The elastic recoil of the machine following this surge may frequently serve to reverse this effect when the weld metal is in poor condition to withstand sudden overloading. These same pressure fluctuations will naturally produce corresponding electrical disturbances, and a paper embracing this phase of the subject would be valuable.

The title of the paper might better have been "The Spot-Welding Circuit" for much of the subject matter may not strictly apply in the case of flash welding which is also a resistance welding process. Regardless of the title, however, the author is to be complimented for a fundamental addition to the scarce literature on the subject.

R. H. Hobrock (nonmember; Bundy Tubing Company, Detroit, Mich.): It is gratifying to see that Mr. Pfeiffer has taken it upon himself to again call our attention to the fact that the resistance-welding circuit as well as the control equipment used in conjunction with resistance welders is in need of further study. Very little has been published on this subject in this country and, although I believe that considerable work is being done in Europe, particularly Germany, not a great deal of the results have as yet found their way into the literature.

The author has mentioned that "the great problem for improvement in resistance welding processes is absolute control of power input to the weld area." This should be emphasized. I have, on several occasions, heard welding engineers describe the ideal control as one which would parcel out exactly a predetermined amount of energy. This is obviously false since the requirement for producing a spot weld is that the temperature of a certain volume of the metal be raised to some value within the welding range of the metal. Whether or not this temperature will be reached is dependent upon the specific heat and specific resistance of the metal, the mass of the metal in the weld area, in some cases on the value of the heat of fusion, and on the temperature gradient between the weld volume and the surrounding metal. The temperature gradient is again dependent upon the heat conductivity of the metal and the shape, size, distribution, and temperature of the electrodes and upon time. Obviously then a given amount of energy, if supplied at low power, may never achieve the fundamental requirement of raising the weld volume of the metal to the temperature required for welding.

The ideal weld control would be some device which permits the current to flow until a predetermined temperature is reached in the weld volume. Two methods have been tried to accomplish this. One method attempts to measure the temperature of the weld volume by measuring the resistance between the electrodes—actually a system of relays opens the primary circuit of the welding transformer when the potential drop across the electrodes reaches a set value. The variable contact resistances between electrodes and sheet as well as between sheets and the variable volume of the material which acts as the electrical conductor are great hindrances to the success of this scheme.

Another method employs the photoelec-

tric cell for measurement of the temperature of the weld spot and through a system of relays controls the flow of current in the welding circuit so as not to exceed a certain predetermined temperature range (see H. Zetzmann, *Archiv f. d. technische Messen*, volume 214, 3, September 1934 and G. Mueller, *Elektroschweiszung*, volume 6, number 1, 1934).

I should like to ask the author why he assumes the volume of the metal carrying the current to be 3 times the volume of the cylinder with bases equal to the diameter of the electrodes and with an altitude equal to the thickness of the 2 sheets, when, from the example of data given, a factor of 2 would be more nearly indicated. Observations made by F. Goldmann (*Elektroschweiszung*, volume 2, page 8, 1931) seem to indicate that the path of the electrical current through one sheet is in the shape of the frustrum of a cone with the smaller diameter equal to the diameter of the electrode. If a cross section of a spot weld is examined and the diameter of the weld spot at the former interface of the 2 sheets measured and if this is assumed as the larger diameter of the frustrum of a cone, the volume of the path traversed by the major portion of the welding current can be calculated. In a few such measurements and calculations made by the author, the factor 2 seemed to be indicated for calculations based on the cylindrical path.

R. A. Gilbert (nonmember; General Electric Company, Pittsfield, Mass.): When the article "The Resistance Welding Circuit," by C. L. Pfeiffer, was published in the August 1936 issue of ELECTRICAL ENGINEERING it was recognized as being of considerable fundamental value; in fact, so much so, that photostat copies were made for our files.

The fundamentals of the welding circuit have been thoroughly analyzed by Mr. Pfeiffer and while it could hardly be expected that such a paper would cover all of the ramifications of resistance welding, we feel that he has provided the ground work for more data in a field where little or nothing is available in the current literature.

There is great need for a handbook or textbook on resistance welding, covering not only the fundamental circuit but also other phases of the art such as welding technique, welding machine design, modern tube control devices, electrode materials, etc.

We trust that such a work will soon be available.

I. T. Hook (nonmember; American Brass Company, Ansonia, Conn.): Mr. Pfeiffer has brought to our attention some important features of the resistance-welding operation. For instance, he places *electrode pressure* on par with current value and time of heat-on period. For a long time, the importance of maintaining the pressure uniform was under estimated. As a matter of fact, in welding low-carbon plain steels, the pressure may vary greatly without seriously impairing the strength of the connection. Steel is weldable over a long range of temperature and pressure. Since common steel was, for the most part, the material seam and spot welded, little attention was given to the maintenance of a constant pressure.

However, with the fabrication of the stainless steels and copper alloys by resistance welding, more precise control over the 3 fundamental variables became necessary. In the case of the copper alloys, a weld was obtainable only by melting the metal. A slight variation one way or the other in the pressure would cause nonfusion, and consequently no weld, or weaken the connection by squirting the molten metal out of the spot forming troublesome cold slivers between the sheets.

With metals which are inclined to be hot short as is the case of some of the newer copper alloys, it is important that the pressure be controlled to a nicety in order that hot short cracks may be avoided in the welds.

The modern machines with air-weighted electrodes seem to fulfil the requirement of exact pressure control.

Mr. Pfeiffer has made it quite clear that exact timing is also important in spot and seam welding. Short time intervals down to that required for a single wave of a 60-cycle current may be an advantage in the case of the copper alloys for 2 reasons (*a*) it avoids heat losses by conduction into the surrounding areas and (*b*) it minimizes the danger of hot short cracks adjacent to the spot besides restricting heat effects to the spot itself.

Mr. Pfeiffer points out that "the best weapons to combat such variables as surface oxides, heat losses to surrounding areas, etc., are relatively high voltages, high current intensities and short time intervals." We believe that the importance of these electrical and timing desiderata has not been sufficiently emphasized.

What we desire above all things is a definite quantity of energy (electrical at the outset converted to a definite quantity of heat energy at the spot) delivered in a short period of time, say $^1/_{120}$ second. By controlling primary voltage, electrode pressure and time, we are attempting to do this. However, this set-up calls for a source of primary energy capable of overcoming high momentary loads which means a relatively high kilowatt-hour rate.

Studies such as Mr. Pfeiffer has given us help greatly in elucidating the problem. Perhaps we shall see, in the not distant future, some more convenient means of delivering definite quantities of energy in a small fraction of a second of time.

G. G. Somerville (nonmember; General Electric Company, Pittsfield, Mass.): This paper presents a very clear and complete theoretical picture of the conditions found in ideal spot and projection welding. The discussion is systematic and straightforward showing a clear understanding of the subject by the author and the writer should be congratulated on his contribution to the art. His attack of the problem and his method of obtaining reliable readings are unique and well worth study by welding engineers.

The practical application of the material presented in the paper by the welding application engineer or welding foreman would present difficulty, however. In practice every welding job is a problem in itself and unless the job is very carefully analyzed the actual voltage, current, and pressure best suited to the problem can be only a guess based on the experience of the supervisor. Many variables enter into the picture such as amount and shape of the material being welded; for example, a steel cylinder extending over one of the welding arms may increase the reactance of the welding circuit to a point where calculated values are useless. Again in practice the ideal spot weld is the exception rather than the rule—generally a great percentage of the welding current is by-passed by previous welds or by the inherent shape of the work. In simple cases the increase in current to compensate for these conditions may be estimated, but in general the proper values of current and time can be determined only by trial.

In a paper such as Mr. Pfeiffer has prepared, it is readily understood that any detailed discussion of problems encountered in practice could not be covered—but it is believed that his paper would be enriched if he included in his summary, a brief paragraph showing where a theoretical attack of some practical welding problems would lead to complications.

D. I. Bohn (Aluminum Company of America, Pittsburgh, Pa.): Mr. Pfeiffer is to be commended for presenting his analysis of the resistance-welding circuit.

The rapid changes in resistance-welding technique, as well as the development of suitable equipment for welding nonferrous materials, has required a more intimate knowledge of the electrical conditions actually existing in this type of equipment than has been known in the past.

I am in hopes that this paper will inspire others of a similar nature in the future.

Mr. Pfeiffer mentions that "it is this condition that makes difficult the welding of materials of high electrical conductivity such as copper, brass, or aluminum, because surface conditions often force the use of currents higher than otherwise necessary with the result that the joint is badly burned when the surface resistance between parts or between electrodes and parts approaches zero." I cannot agree with this general statement regarding aluminum, as, with suitable equipment, aluminum is being spot and seam welded commercially with results comparable to those obtained with other materials.

This welding is done without any burning or pitting of the surfaces, and, where desired, one of the surfaces may be welded so that the weld is practically invisible.

Bela Gati (Katona Rail Welding Concern, Mount Vernon, N. Y.): The author's comment that "the lack of available literature on this subject inspired the preparation of this paper" is very significant to me since this scarcity is especially evident in European and other countries. I have, in the past, been able to get copies of such papers for a quarter and have found it advisable to send such copies to my boss. It is not considered good practice in the Orient to send an article torn out of ELECTRICAL ENGINEERING, but when I send the whole issue, it gets passed on to a subordinate due to the boss's lack of time and the need to have a subordinate study the other articles contained therein.

The present article is already being studied by the Katona Concern. This concern has arc welded 25,000 rail joints in Hungary and some hundred test joints in other countries. I realize that about 10,000 welded rail

joints have been made in the United States in tunnels and on bridges and that most of these are made by the thermit process and were not made during traffic. I would like to inquire whether the author has had any experience with the resistance welding of rail joints. I would like to make a general inquiry as to whether the Sperry Company could furnish such information and also if any information is available on the mystic infrared X-ray welding of Doctor Longoria.

One hundred million rail joints need to be welded, and this should give work to 100,000 welders for a year. At the present time the battering of steel rail ends in the United States so affects their life as to cause them to last only 5 years and this would be much shorter in case of war. North America might lose such a war because of the failure of her unwelded rails; thus good maintenance of her railroads may be even more important than the acquiring of very costly battleships.

C. L. Pfeiffer: I am pleased by the general comments given in all the discussions which emphasize the need for investigating the weld area more thoroughly.

I agree with Mr. Heitman that in most cases the impedance of the leads and transformer is the determining factor in determining the current through the weld and that this is mostly reactance. I also feel that it is usually desirable to have high impedance in the leads and transformer as this acts as a stabilizer and sometimes brings definite rewards in weld quality. The question of electrical efficiency in the weld circuit is often quite secondary to quality in manufacturing operations especially on lower kilovolt-ampere welders. The little data that was given was in connection with relatively low kilovolt-ampere welders having short leads.

Mr. Zimmerman's reference to fluctuations in electrode pressure during the welding interval is an interesting problem for investigation and no doubt would require an ingenious set-up for accurate measurements in short intervals of time.

Mr. Cogan's remarks indicate that he appreciates even an approximate rule-of-thumb method which allows a sufficient factor of safety in determining voltage drop in the weld area and which may be used as a starting point in the design of a welding machine to be used on a specific job. The factor of 3 given in the paper includes a factor of safety for design requirements and should answer Mr. Hobrock's question as to why 3 is used when 2 appears to be more nearly correct.

In connection with Mr. Dawson's comments on oscillographic measurements, not enough data is at hand to say what voltage variations there are in the weld area, although on copper-rod butt welding I can say that no appreciable change was noted on any of hundreds of oscillograms. The references to Jean's formula and related matter are simply suggestions because the whole problem is one of groping around for a possible line of attack. The vector diagrams represent actual vector values for all quantities except E_T which is obtained by subtraction as mentioned and because of the angular relationships can only fit in one way. I agree with Mr. Dawson that definite energy input into the weld area cannot be generally used and only works out in a practical way by the use of ignitron or thyratron control. Because of variable contact or material conditions it is important to know when occasionally a weld or poorer quality is made and this might be accomplished by measurement of voltage drop and current values by an instrument which indicates or reports an off-normal condition. This weld can then be put aside as being questionable. Mr. Hobrock's discussion of energy control into the weld area is correspondingly interesting.

To supplement Mr. Woofter's remarks I wish to point out that figure 4 was made and an example given to show primarily what should not be done, and that the other circuits, figures 5, 6, and 7, are far superior.

In my references to difficulties in welding "materials of high electrical conductivity such as copper, brass, or aluminum" I did not wish to give the impression that there is much trouble in welding aluminum as questioned by Mr. Bohn, but instead that one must be more alert in making machine adjustments and have better welding equipment than in welding low-carbon steels.

Mr. Frost's discussion presents a very clear picture of the input energy and loss factors involved in spot welding and I wish to compliment him in presenting an equation which is a good starting point for nearly any further investigation of the weld area.

I am not in a position to discuss resistance welding of rails or Dr. Longoria's secret process as mentioned by Mr. Bela Gati. Offhand it seems to me that the flash welding of rail ends in the field is a problem of having portable equipment of sufficient capacity available in remote places. Certainly a power supply of perhaps between 1,000 and 2,000 kva to be made available just anywhere along a railroad is a problem by itself.

Further comments on remarks by Messrs. Gilbert, Hook, and Somerville are hardly necessary. Of course I agree with Mr. Somerville that an entirely "theoretical attack of some practical welding problems would lead to complications." At a given voltage the welding machine will duplicate its work time after time providing the parts fed to it are uniform in every respect. One hundred per cent uniformity in fractions of a thousandth of an inch, in surface condition, or contact area is practically impossible. These small variables are not usually of major importance on most jobs but the welding engineer must recognize them, and on critical jobs the design of parts, materials, the type of machine, tools, and control, must be such to reduce possible variations to a minimum.

In conclusion I wish to thank the various discussers for the time spent in examining my paper and preparing their discussions.

Proposed Transformer Standards

Discussion of a paper by J. E. Clem published in the January 1937 issue, pages 32–36, and presented for oral discussion at the selected subjects session of the winter convention, New York, N. Y., January 25, 1937.

S. I. Oesterreicher (Metropolitan Device Corporation, Brooklyn, N. Y.): I would like to discuss Mr. Clem's paper on the proposed transformer standards and in particular that section which deals with current limiting reactors.

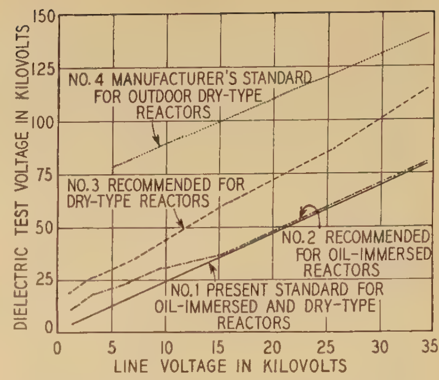


Figure 1. Standard dielectric test specification for current-limiting reactors

The paper recommends certain insulation requirements for oil immersed and dry type reactors. I believe the values given in table IV are conservative and there should be no difficulty in complying with the suggested requirements.

Up to the rated voltage limits given in table IV, dry-type reactors are used for both indoor and outdoor service. Therefore, it should be made clear whether or not the given values apply to both kinds of service. I believe that for outdoor service we can afford to increase the low-frequency applied voltage tests to higher values so as to be better than the transmission line. To summarize the past and proposed test potentials, I have prepared a diagram which shows the practices followed for the various kinds of reactor services.

However, it is misleading to believe, that due to the new and higher test voltage requirements the reactor will automatically become a superior product. The recommended low frequency dielectric strength requirements are easily met by providing the proper supporting insulators. But this leaves the reactor winding in the same dielectric test muddle as it has been in the past and as stated in the Institute Standards, section # 13, namely: "although it is generally recognized that a test between turns is desirable, no rules have as yet been established." It is not to be thought that because no rules have been set as yet, the designer has an easy task—on the contrary his job is the more difficult. One purchaser specifies a 40-kv high-frequency test for a 13.2-kv line. Another is satisfied with 56 kv on a 24-kv system. One wants a 100-kv impact test with a steep wave front. Not so long ago a $^1/_4$-cycle front on a 60-cycle system was considered steep. Nowadays we speak of wave front in fractions of microseconds, etc. To correct these inconsistencies, I would suggest Mr. Clem and his associates on the transformer subcommittee tackle also this phase of the standardization rules and recommend certain minimum requirements and some uniform procedures which will give us a guide for testing reactors on a more equal basis.

I noticed in the report that the committee changed the classification of the reactors to that of oil-insulated and air-insulated reactors. I would suggest that the present classification namely, oil-immersed and dry-type reactors be retained.

K. B. McEachron (General Electric Company, Pittsfield, Mass.): The use of the rod gap as a means of determining the potential to be applied to transformers when undergoing impulse test is not a very satisfactory means of determining test conditions.

The volt-time spark-over curve of the rod gap is very different in shape from the volt-time breakdown curve of transformer insulation. Furthermore, since the transformer insulation strength is not affected by external atmospheric conditions, and the rod gap is so affected, it would appear that the use of kilovolt crest for a given wave shape would be more satisfactory. Thus, the crest value and wave shape without respect to polarity would be specified for each rating of transformer. If it is desired to spark over a parallel rod gap as in test (*a*) of the paper, its spacing would be adjusted to correspond to the existing conditions of humidity, air density, and polarity.

The change from inches of gap to kilovolt values should not now be difficult, since data agreed upon by the various American laboratories are available for both polarities, and corrections for atmospheric conditions are pretty well agreed upon. It seems to me that there is no very good reason for continuing the use of inches of rod gap as a standard, when kilovolt crest values are much more fundamental and can be regarded as a true standard.

For other wave shapes than the standard $1^1/_2$x40, sufficient data concerning the volt-time breakdown curve of transformer insulation are becoming available, so that the proper kilovolt value can be readily chosen. I would like to recommend to the transformer subcommittee that serious consideration be given to the use of kilovolt values rather than inches of rod gap.

In making the impulse tests which have been called for, upon transformers, one rather serious difficulty has arisen, which has increased both the time and cost of making the required tests. I refer particularly to transformers having more than 2 windings, in which case one winding will be utilized for excitation at normal frequency and potential. The winding under test will have one terminal grounded, the impulse being applied to the other end of the same winding while any other windings (and there may be several, particularly if the transformer is 3-phase) will have an air gap connected across each terminal to ground. Quite often these gaps spark-over, and the sudden change of constants affect the wave shape of the impulse applied to the winding under test in an unpredictable degree, and at the same time power follow may take place across the gaps. To prevent such power following, lightning arresters are frequently connected to ground from the terminal of each winding not under test. This is not a complete answer, however, partly because of the multiplicity of arrester ratings required, and partly because the arrester's resistance is nonlinear, being infinite until the gaps spark over, dropping to a low value which increases as the current decreases.

A considerable improvement in testing technique would result if a resistance of proper ohmic value could be connected between each terminal of windings not being tested and ground. This, however, is impractical as long as the power-frequency excitation is a required part of the test, since the energy loss in the resistors is very high. This situation is somewhat improved by the use of a high voltage fuse in series with the resistance and having a series gap just great enough to prevent the normal-frequency excitation potential from putting the fuse into the circuit until the arrival of the test impulse.

A solution of this problem, it seems to me, would be to make the 3 tests as now outlined in Mr. Clem's paper, without the use of power excitation, and follow with a fourth test with normal excitation with the applied impulse reduced to a level just below the spark-over values of the gaps in parallel with the terminals of the winding or windings not being tested. For this last test, the resistor which had been bridged across the bushings for the 3 previous tests would have been removed. Such a procedure would greatly facilitate the test, since the proper impulse-generator constants can be set up in advance using the transient analyzer (The Oscillograph Electric Transient Analyzer, N. Rohats, *G. E. Rev.* volume 39, 1936, page 146), since the transformer constants would not change due to the flashover of gaps connected to windings not being tested.

I. W. Gross (American Gas and Electric Company, New York, N. Y.): I am sure we very much appreciate the efforts of Mr. Clem in studying in detail the proposed transformer standards and pointing out those features which are outstanding, so far as suggested changes or revisions are concerned, before they are written into the standards with which we may be tied up for some period of time in the future.

There are several comments I would like to make on this paper: first, in regard to the rated circuit voltages listed in the first columns of tables I and VI, I think the setup of both tables would be much simplified by omitting voltage classifications where no data is given, such, for example, as voltage ratings of 120, 240, 480, 2,400, 4,160, and 4,330. It is not clear why these have been included in the table and it would seem to be a very simple matter to footnote this column to indicate that transformers to be used at rated circuit voltages which were not listed would fall in the class of the next higher voltage class.

In table VI, also, the voltage rating of 2.5 kv is given but data are not given for bushings in this voltage class. Either this voltage rating should be omitted or proper data should be inserted in the table.

Another point which has continually come up for consideration is the designation of impulse strength of transformers. I note that specifying impulse strength in terms of inches of gap is still retained to the exclusion of any other method. In table I, the value of the impulse characteristics of transformer insulation would be very much enhanced if the so-called "basic insulation level" were given in kilovolts. This does not mean that the tabulation of gap spacing need be omitted, but I feel very strongly that the kilovolt values should appear. At the present time, there is no tie between the inches of gap spacing given in table I and the impulse strength of the transformer without searching the literature for the corresponding impulse strength of the gap levels indicated. Such an omission in "Standards" is going to be decidedly burdensome to those who have frequent occasion to design a protective system in conjunction with either lightning arresters or gaps in their various forms.

It cannot be too strongly emphasized that the gap is only a test device for applying voltage under specified conditions and has impulse characteristics quite different from fibrous transformer insulation. For example, the gap spacings given in table I are suitable only for positive waves; for negative waves the spacing must be changed. For fast rising waves, the gap permits higher voltages on the transformer, even to the point of exceeding the transformer ultimate strength. To adopt such a test device as a basic insulation level for transformers seems fundamentally unsound.

Commercial impulse tests on transformers have now been made for a period of several years, and in our own company such tests are usually made on all large high-voltage transformers. In this connection, I wish to point out that the procedure indicated on page 33 under "Impulse Test on Transformers" is, at present, rather confusing. Apparently, the intent is to apply 3 impulse waves; one, a full wave; one chopped on the tail (by gap flashover); and one chopped near the crest (by bushing flashover). If these waves were definitely specified as to the crest kilovolts, with tolerances for time at the instant of flashover, I believe the situation would be fully covered. It seems the logical way to define a test voltage is by magnitude and duration, leaving to the test code such problems as type of equipment to use for the test and the conditions under which they are to be made. Another point in connection with items (a), (b), and (c) referring to the application of the test wave, shows that 2 voltages are applied under the existing conditions of humidity, and air density, and another test under standard conditions. Under these conditions, therefore, the transformer winding will receive a voltage test depending, to some extent, upon weather conditions, and there seems to be no justification for this. I would suggest that all impulse tests be made under definite standard conditions. This again would be accomplished if the test voltages were specified in terms of volts and time rather than in terms of the device used to make the test.

I believe this section on the impulse test data on transformers could be, and should be, very much clarified before being written into the permanent standards.

A New Electrostatic Precipitator

Discussion and author's closure of a paper by G. W. Penney published in the January 1937 issue, pages 159–63, and presented for oral discussion at the selected subjects session of the winter convention, New York, N. Y., January 25, 1937.

R. E. Hellmund (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): The rather brief reference in the paper to the beneficial effects of the electro-

static precipitator upon those suffering from allergic conditions conveys very little idea of the very important part which this device may play in the relief of such suffering. An allergic condition as referred to in the paper simply means a supersensitiveness which some persons have to certain substances which they eat or with which they come in contact in other ways. If these persons breathe air containing substances to which they are supersensitive and which in the majority of cases seem to be of an organic nature, it results in the irritation of the nose, throat, or eyes so familiar to victims of hay fever. If the bronchial tubes are sensitive, the result will be asthma, either of the hay-fever type caused by pollen in the air, or of a type caused by other substances. It is claimed that even certain skin irritations, such as eczema, are caused by similar conditions. Asthma, in particular, seems to be caused to a great extent, although by no means exclusively, by something emanating from moulds or fungi growing in damp places. One method of cure consists in innoculating the patient by hypodermic injections of the particular substance to which he is supersensitive. However, the number of cures claimed by this method is small because so few of the substances likely to cause these allergic conditions are known at this time. In view of this, it is at once evident that this electrostatic precipitator offers relief to a great many people. It is claimed that about 15 per cent of the population (about 20,000,000 in the United States) are suffering from some allergic condition or other, and it seems that only a small percentage of these are affected by substances other than those conveyed by the air.

In view of the prevalency of asthma in Holland, a chair for the study of it was created in the University of Leyden several years. Dr. W. S. van Leeuwen, following some original work done in America, obtained some very excellent results. He was the first one to experiment with means for cleaning the air to bring about relief. He arranged for air intakes a considerable distance above the ground and used large amounts of cotton as filtering material. In some cases this yielded very good results to those who spent their nights in these rooms and went about their regular duties in the daytime. However, in other cases he failed to get results, though his analyses had shown that they were also due to substances conveyed by the air. It is well known that air even at considerable height contains particles of organic materials, and from Mr. Penney's investigation it is evident that the cotton was effective in removing only some of the larger particles; as a consequence, those sufferers affected by the smaller particles naturally did not obtain relief. It is in this connection that the electrostatic precipitator is likely to be of great value. As indicated in the paper, some astounding results have been obtained with it and comparative experiments on patients have definitely proved its superiority over the mechanical filter; in fact, it seems to give almost 100 per cent results in cleaning the air.

There are some persons, however, who are affected by dust or other irritating substances located in wearing apparel, bedding, etc. Dr. van Leeuwen has, for instance, established as a cause certain moulds growing on the feathers in pillows in damp localities. Such substances can, of course, reach the breathing organs through air which immediately surrounds the sleeper and which has not been passed through the precipitator. Again, such substances as face powder, dandruff, and the like have been suspected as possible causes, and here it is again impossible to accomplish complete filtering before the particles enter the patient's breathing organs. However, with the many substances eliminated which can be filtered out by the electrostatic precipitator, the remaining possible causes are narrowed down to a very few, thus making it relatively easy to determine what they are and to eliminate them from the living quarters of the sufferer. Dust particles, in addition to causing allergic conditions, are quite generally assumed to carry certain bacteria, and therefore their elimination may also lessen the danger of contagious diseases caused by germ-laden air.

Myron Zucker (The Detroit Edison Company, Detroit, Mich.): Mr. Penney calls it a precipitator, but its real meaning would be brought home better if he called it a filter.

Mr. Penney's development is of great interest because of the fields it opens. The 2 major contributions seem to be the practical elimination of ozone (which is now considered an active poison), thus permitting the use of the cleaner for air conditioning; and increased economy. Since no costs are given, however, it is difficult to imagine just how widespread the precipitator's use might become. Would the author give some orders-of-magnitude for initial cost, power demand, and power consumption for sizes ranging from his window air filter up through 500,000 cubic feet per minute in plants?

Also, similar figures for physical size of the units, and the corresponding gas velocities to be used for satisfactory filtration would help orient the field for this precipitator.

Have any tests been made for ionization remaining in the cleaned air? It might be a favorable by-product in case researches now being conducted show that ionized air is healthful.

E. M. Strong (Cornell University, Ithaca, N. Y.): The author has produced a very commendable improvement in the technique of electrostatic filtering. A really effective dust remover has enormous possibilities in many fields and in large quantities. I am interested especially in the field of hay-fever treatment which the author mentions. While this is an allergic affliction and therefore concerned with food and other factors in addition to dust and pollen, it is true that removal of these particles is a major preventive. The author may very well initiate a humane service in this field which involves a large share of our population.

There are 2 major objectives indicated by the author in the development of his precipitator:

1. Reduction of power and space required
2. Reduction of generation of unhealthful products

It is regrettable that more definite quantitative data are not given in the paper to show just how well these objectives were realized. I would inquire what power is used by the models now built and how it is proportioned between ionizer and precipitator.

The generation of unhealthful products seems to me a matter of major concern and one which demands thorough investigation before the apparatus is made available to the general public. So far as I am aware, our knowledge of the effects on the health of humans, exposed for long periods to the products of corona in confined air, is very meager.

One very logical application of the apparatus illustrated by the author is in the air circulating system of the modern air conditioning unit for home or other use. With customary high percentage recirculation it is conceivable that the "very low generation" of unhealthful products may well accumulate to sizeable and definitely dangerous proportions.

If the author has as yet any data on this aspect of the application of the precipitator, surely they are of major importance; if not, I would urge that a careful study be made into the consequences of long-time living with the apparatus before it is put on the market.

G. W. Penney: Mr. Strong and Mr. Zucker asked for definite figures on the size of the unit and the reduction in size as compared to the previous precipitation practice. This is frequently given in terms of precipitation time. The precipitation time which we have used varies from 0.12 seconds to 0.6 seconds, depending on the application. In other words, a precipitator to handle 3,000 cubic feet per minute would occupy a volume of 6 to 30 cubic feet. From published figures I believe that the precipitation time in older practice has been of the order of 5 seconds, which would correspond to a precipitator volume of 250 cubic feet to handle 3,000 cubic feet per minute. These volumes refer to the actual volume occupied by the precipitator proper and does not include any space occupied by ducts.

The high-voltage power consumption is approximately one watt per 100 cubic feet per minute. For the 3,000-cubic-foot-per-minute unit referred to above, the transformer and tube losses amount to about 30 watts so that the total power consumption is about 60 watts.

There is apparently no disagreement as to the harmful effects of the amount of ozone present in the air from the older precipitators. However, I believe that the danger from minute quantities of ozone is frequently exaggerated. There are many things which are essential to life in certain concentrations but which are very harmful in excessive concentrations. In discussing this question with a number of doctors, they have all agreed that ozone is probably beneficial and certainly not objectionable as long as it is present only in a concentration not exceeding that found in outdoor air.

The generation of ozone is controllable over a considerable range, although a unit for very low ozone generation is somewhat more expensive. The ozone generation which we have regarded as the allowable limit is based on the same premise as that suggested by Mr. Strong, which is that when used in a house with full recirculation,

the natural infiltration and the decomposition of ozone must keep the ozone below any objectionable limit. We assume that the ozone is not objectionable provided that its concentration does not exceed that present in outdoor air in bright sunshine. Our measurements give the ozone generated as less than one part in 300,000,000 parts of air. However, methods for measuring such minute quantities of ozone may not be entirely reliable in giving the absolute concentration, but at least the comparison between outdoor air and the air from the precipitator should be reliable.

Mr. Zucker asked for cost figures. This device has been produced in relatively small quantities to date so that manufacturing costs are not stabilized, so that for the present we can only quote prices on specific applications. However, when manufacturing methods are developed for quantity production it is expected that the cost of equipment for cleaning the air in a house should be comparable with the cost of the household refrigerator.

In reply to Mr. Zucker's question as to the ionization remaining in the cleaned air, there is some residual ionization and this can be varied over a wide range but our present viewpoint is that this ionization probably does not have any noticeable effect.

Studies of Stability of Cable Insulation

Discussion and authors' closure of a paper by Herman Halperin and C. E. Betzer published in the October 1936 issue, pages 1074–82, and presented for oral discussion at the selected subjects session of the winter convention, New York, N. Y., January 25, 1937.

T. B. Jones (The Johns Hopkins University, Baltimore, Md.): At The Johns Hopkins University studies are in progress dealing with the nature of the radial variations of power factor as affected by oxidation of the compound and by the type of metals used as electrodes. By varying the amount of oxygen in the compound it is possible to obtain rising power factor-time curves with very high values of power factor at elevated temperatures in the vicinity of 80 degrees centigrade. However, when the specimen has cooled down and radial power factor measurements are made it is found that the average of the radial curves does not differ greatly between good specimens and deteriorated specimens. This is in agreement with the authors' table I. Since the radial measurements indicate the degree of "solid" loss then the difference between the average value of the radial tests and the final over-all value of power factor of the sample before dissembling should give an indication of the interlayer or ionization losses. I would like to know if the authors have made any determinations of this nature and if such results correlate with the ionization factors of the complete samples.

The ionization factors in table I are taken at room temperature. Is there any change in ionization factor with increase in temperature? Our results indicate ionization factors as high as 0.006 at 80 degrees centigrade whereas when the temperature is reduced to 25 degrees centigrade the ionization factor is zero. Moreover the final over-all values of power factor at room temperature do not differ greatly among good and poor samples, this would seem to indicate that the high losses occurring in samples with oxidized compound can in all cases be associated with elevated temperature.

W. A. Del Mar (Habirshaw Cable and Wire Corporation, Yonkers, N. Y.): Load cycle life tests are the penultimate tests of cables, the ultimate tests being, of course, actual service under proper supervision.

The company with which I am associated has used and continues to use such tests for comparing different cable oils, papers, and designs. Formerly the criterion of these tests was the number of cycles until failure occurred. Tests on this basis often lasted for several months and as the capacity of the equipment was necessarily limited, the number of tests that could be made per annum was not very great. Thanks to Messrs. Halperin's and Betzer's work, this condition has been changed and a great many more tests can be made in a given time. This is accomplished by establishing a number of arbitrary test limits and stopping the test when any one of these has been reached. These test limits include power factor, temperature, and ionization, as well as life. The limits are chosen by experience to distinguish a cable that is practically stable from one that is unstable.

Messrs. Halperin and Betzer choose a test voltage of $2^1/_2$ times the working voltage. I think that it would be more revealing if they said that they use a maximum stress of 234 volts per mil (calculated by the simple logarithmic formula). Using this stress it is possible to practically parallel Mr. Halperin's results using cable of different design, for instance, thinner walls at lower voltages and indeed, this is what we do in our standard tests, using 220 mils of insulation.

Mr. Halperin's tests were made on horizontal cable, whereas some tests by Detroit Edison Company were made on vertical loops. We have made tests both on vertical U's and horizontal lengths and find that quite different results are obtained. There is some question as to which type of test gives the more reliable results, i.e., results most consistent with operating conditions. However the test is made, it seems important to have the ends horizontal, so that the oil in the end paper (where there is no lead sheath) will not drip into the remainder of the cable.

There is difficulty in obtaining consistent results on a number of apparently identical cables and until this has been removed, some suspicion attaches to the validity of all these tests. We have made series of 4 cables of apparently identical materials, given identical and simultaneous treatment under the most carefully controlled laboratory conditions and yet the cables, on test, will show different results. Dr. Whitehead's voltage-time tests on laboratory prepared cables showed similar divergencies. In those tests only 15 layers of paper were used, so that differences in paper density might not have been averaged out, but in our tests, there are normally at least 36 layers of paper, so that the probability of many low-density spots being superimposed is rather remote. Nevertheless, we find that the variance is much less with high than with low-density paper.

Mr. Halperin has spoken of the better results given by cables impregnated with rosin-blended oils. We have found that such cables exhibit better adhesion of compound to the paper and are less subject to excessive drainage. The use of rosin, however, is advantageous only with certain types of oil, instability resulting from its use with certain naphthene base oils now advocated for cables.

G. M. L. Sommerman (American Steel & Wire Company, Worcester, Mass.): The results presented by Halperin and Betzer show that cables made under identical conditions of fabrication, but with different saturating materials, possess widely differing values of stability and life. This leads to the general conclusion that the problem of finding stable impregnating compounds is fully as important as the problem of reducing deteriorating influences by the use of improved methods in the manufacture of cables.

Load cycle life tests indicate whether one cable is better than another, but, in themselves, give little information as to why it is better. Various methods of diagnosis, such as the dyeing of tapes and the radial power factor test, indicate reasons for superiority more clearly. The authors are to be commended for their discovery of a correlation between life and the quantity: inch-hours of vacuum maintained by the cable. In order to determine the ultimate basis of superiority, however, the materials used in cables must be subjected to various simplified tests, each determining some isolated characteristic. The results of these simplified tests must then be correlated with the observations covering load cycle life tests. As an illustration of this, it has been found by simplified tests made in our laboratory that there are at least 3 advantages accruing from the use of rosin in impregnating compounds, in addition to the obvious effects arising from the increased viscosity of such compounds.

It is now being more generally recognized that the stability of insulation and the properties after some service are more important than the initial properties. This should have an effect on the choice of cable saturants. The use of rosin in the saturating compound is a case in point. Many cables made 5 to 10 years ago contained from 5 to 15 per cent rosin in the saturant. Because the rosin then in use was relatively crude in form, these cables had maximum power factors of the order of 2 per cent (at 85 degrees centigrade), while cables containing no rosin had lower power factors. Although it was realized in a general way that rosin stabilized the insulation, there has been a general trend away from its use during the last 6 years—mainly because of the lower initial power factors obtainable by the use of straight oils. The load cycle life tests made prior to several years ago were so accelerated (employing voltages from 3 to 10 times the rated values) that differences in dielectric loss were greatly magnified. Because of these exaggerated conditions, the probability of thermal instability in test was high for the rosin-containing

cables, and these cables consequently showed up rather poorly. The load cycle life test has, from its inception, enjoyed such prestige that the results were allowed to subordinate the results of electrochemical stability tests and cable operating records.

In the last few years, 2 things have occurred. One has been the development of improved rosins and the use of these rosins in cable saturants, with the result that the cables so made have power factors little if any higher than those of cables made with straight oils. Another has been the improvement of load cycle life testing procedures which are less accelerated in character, and which yield cable failures approximating those occurring in service. The work of Halperin, Betzer, and their associates is an important contribution to this latter field. As a result of these developments, both of which have made thermal instability improbable in the life tests, the more stable characteristics of rosin-containing cables have become manifest. In view of this, it would not be surprising to see a trend back to the greater use of rosin or similar addition agents in the saturants of paper-insulated cables.

M. G. Malti (Cornell University, Ithaca, N. Y.): Various writers, [1,2,3,4] on dielectrics have ascribed the breakdown of dielectrics to heat, asserting that electric breakdown is essentially a heat phenomenon. Over 9 years ago, in a paper,[5] I asserted that the absence of valuable data on the nature of dielectric breakdown with alternating potentials renders the formulation of a theory, or even a definition thereof, a matter of wild conjecture. I further disagreed with the propounders of the so-called pyroelectric theory of breakdown on the following grounds:

(*a*). The energy dissipated in the period from the time of voltage application to the time of breakdown, does not raise the temperature sufficiently to account for a breakdown due to heat

(*b*). Actual temperature measurements[6] show that no temperature rise exceeding 10 degrees centigrade does occur in glass before rupture.

The results of the present paper[7] furnish excellent evidence against the pyroelectric theory. Indeed that the breakdown of a solid dielectric cannot be a heat phenomenon is shown by the following facts brought out by the paper:

1. The fact that power factor is sometimes lower at high temperatures than at room temperature (see reference 7, figure 1).

2. The fact that breakdown is always accompanied with a change in the physical condition and chemical composition, and that no breakdown occurs except where such a change shows up (see reference 7, figure 5).

3. The fact that breakdown sometimes takes long paths (over 5 feet as shown by reference 7, figure 7). Indeed if breakdown were simply a heat phenomenon, it would occur where heat would be concentrated, that is, over short paths.

4. The fact that breakdown sometimes starts at the sheath (reference 7, figure 7) where presumably the cable is coolest.

5. The fact that it takes "ageing" to reveal weakness and that different samples presumably subjected to the same heat show no failure unless chemical and physical changes occur (see figures 1 and 5 and conclusion 13 of reference 7).

6. The fact that the authors have observed (see conclusion 6, reference 7) that *ionization* not heat is the cause of deterioration which ultimately results in failure.

7. The fact that stability of the impregnating compound (not heat) is a primary factor in insulation deterioration (see conclusions 5 and 10).

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R. J. Wiseman (The Okonite Company, Passaic, N. J.): In stability tests on cables we are largely concerned with small movements or migrations of the free oil, that is, the oil between the paper tapes, in the gaps between the paper edges, and the oil between the strands of the conductor. For this reason, the amount of oil which flows longitudinally into or out of the joints is of importance in determining the life of the cable. However, because this is such a variable factor, and because the section of a long cable farthest from the ends is the most isolated, and usually the most liable to breakdown on stability test, it appears to be preferable to seal the ends of the cable as completely as possible. The authors' cable joints were designed to prevent longitudinal flow and this was "closely approached," but not "completely achieved." What tests were made to check the amount of longitudinal flow?

If this lengthwise flow is eliminated, then stability tests on 50 foot lengths of cable, or even somewhat less, are practical. The cable should be long enough to include in a representative way those slight irregularities which are the reason for breakdown initiation at one point rather than another, and so that the effect of the inevitable loss of a few drops of oil at a splice or insulating joint is insignificant.

If the length of cable under test has the ends perfectly sealed, the only oil movement when the cable is heated is a radial movement, which expands the sheath. If the sheath expansion is measured at different points around the circumference, and at intervals along the length, very considerable differences will be found in sheath expansion. Even with pressures of 40 or 50 pounds per square inch inside the sheath, there may be a decrease in diameter along one axis. The differences in sheath expansion probably account for the unequal stability of samples 60 and 61, which were identical except for being sheathed separately and with different kinds of lead.

The difficulty of predicting failure by making periodic power factor tests is well illustrated by the radial power factor tests made on a few inches of cable involved in incipient failures. Take the case of curve *H*, figure 3, where the carbon extended about 30 per cent of the distance from the conductor to the sheath. The radial power factor curve shows the remainder of the wall to be in good condition. It is easy to estimate approximately the effect of the high power factor of this short section on the average power factor which would be measured on a reel length of cable. Suppose 50 per cent of the insulation was broken down completely, then this whole section would be at conductor potential and except for the increased stress on the good 50 per cent remaining, its power factor would remain unaltered. So that if 50 per cent of the insulation was completely broken down, there would be no appreciable change in the average power factor of the cable.

If this 50 per cent, instead of being completely short-circuited, had its power factor increased 40 times, the power factor of the short section under consideration would be about 10 times what it was before. If this section was about 6 inches long, this effect would be lost in a 500-foot length, for it carries only 1/1,000th of the total capacity current, and the power factor would only be increased by 10/1,000th or 1 per cent of its previous value. Such a small increase is completely masked by temperature changes and other effects.

On this account, the authors have made their power factor measurements on 25-foot sections, but the introduction of insulating joints is open to objection, chiefly because it disturbs the cable. A better method for locating incipient failures and testing longitudinal uniformity is to measure the temperature rise along the sheath with thermocouples at points located 2 or 3 feet apart. If the power factor of a few inches of cable increases 10%, the heat generated in that section will increase 10 per cent and the sheath temperature would increase 10 per cent were it not for heat conduction along the cable. If a 66-kv cable is held at say 115-kv with a similar dead cable alongside for use as a temperature zero level, then the heat of dielectric loss will give a temperature rise of something like 3 degrees centigrade for a 66-kv cable with a 0.0035 power factor. A one-degree-centigrade rise above normal at a point on the sheath represents a "hot" spot, and by making careful measurements the point of failure of a cable has been predicted a month before breakdown occurred. This would have been impossible with power factor measurements.

It is important to decide whether the quality of a cable is to be judged by the interval between the start of test and the time when instability sets in, or if the time to failure is to be used to make comparisons. Figure 4 shows that class *A* and class *B* cables could easily be distinguished from the other classes by the small increase in power factor at elevated temperature. The actual time to failure, once failure has set in, does not seem so important, for conditions might be very local at the fault. Probably the best way to compare cables on stability tests is to make sheath tempera-

ture or "hot spot" measurements at 2-foot or 3-foot intervals along the sheath, and to use the curves of sheath temperature rise versus length, obtained after a standard interval of say 2 or 3 weeks to grade the cables. Whereas figure 4 shows that grade *B* cables had similar average power factors to grade *A* cables, the local deterioration which was found in grade *B* cables, and which is evident from figure 5, would become apparent from sheath temperature measurements.

It is quite possible that simultaneous voltages and load cycles are not necessary. The power factor of the cable could be tested with no more end preparation than is used for routine tests at the factory. Load cycles could be applied, followed by a final high-voltage test for making sheath temperature measurements. The oil movement caused by the load cycles is responsible for the formation of the ionizable voids and consequent increase in power factor, and the authors have shown in figure 3 that the carbonized areas created by the high voltage, contribute very little to the power factor in the earlier stages of the test.

The difficulty of correlating power factor tests with cable condition is increased by the difficulty of controlling the ambient temperature. A change of a few degrees in the room temperature may change the oil pressure in some cables from a good vacuum to a few pounds above atmospheric and this will have an important effect on the measured ionization. It is also tied in very closely with the effect of previous heat cycles on sheath stretching and it may be that a hot spot or local deterioration originates at a point where the sheath expansion is abnormal. The sheath stretches most where, measured around the circumference, there are the longest sections of thin lead.

The improved stability resulting from the use of paper and oil which are gas free, is well illustrated in the authors' paper. The reason for this is not as obvious as it might seem, but it is probable that in a highly degassed cable, the oil returns radially inward on cooling in a continuous unbroken column, and the voids are created near the sheath, where the stress is lower. If this is the case, we should expect that in class-*A* and *B* cables, failure would initiate at the sheath, whereas it would commence at the conductor in the poorer classes. An examination of figure 7 shows samples 24 and 64 (in class *B*) apparently do belong to the sheath failure class, whereas in samples 97 and 114 (in class *D*) the breakdown evidently initiated at the conductor.

It is said that the primary cause of failure is the bombardment of the compound by ionization in gaseous spaces. Is not the primary cause rather the production of ionizable spaces? The most effective method of improving high voltage cables is not in finding a compound which will withstand bombardment, or evolve a minimum of gas, but to prevent or minimize the formation of these ionizable voids in the first place, or else to restrict their formation to a part of the cable which is not under stress.

When a sheath failure occurs which is not accompanied by insulation breakdown, repairs are made in the manhole or shop. The cable insulation is removed until all traces of moisture is eliminated. It is difficult to decide whether a tape is moist or not by its appearance, and power factor tests are not practicable under such conditions. However, high-voltage d-c tests on paper tapes are said to be a good indication of the presence of moisture and are easily carried out on portable apparatus.

The article proves the value of stability tests to determine the ability of the cable to operate satisfactorily in service. Some manufacturers have been making these tests for a long time, and have found them invaluable in arriving at the operating characteristics of new types of cable.

Herman Halperin and **C. E. Betzer:** In reply to T. B. Jones' question, the results of power-factor measurements of individual tapes when properly averaged give the power factor of the cable as a whole at sufficiently low voltage to avoid ionization providing that conducting paths have not formed in the insulation. Such paths do not necessarily have the same effect in the test of individual tapes as in the test of the complete cable.

We have noted in a previous series of aging tests of 66-kv cable that in most cases ionization factors increased with increasing temperature but in a few cables the reverse was true. We have no explanation for this phenomenon. In the tests covered by this paper ionization measurements were made at room temperature only.

Although the point is not emphasized in the paper, we are pleased to have W. A. Del Mar point out again the fact that aging tests need not be continued to failure.

His suggestion that the test voltage be expressed in terms of maximum stress is in general agreement with our statement that for cables to operate at less than 66 kv the ratio of test voltage to operating voltage might be more than $2^1/_2$ on account of the relatively low operating stresses. Voltage tests in general are based on average stresses instead of maximum stresses in the insulation and probably the same should apply to aging tests.

In connection with the differences in test results for apparently identical cables it should be noted that such cables often differ widely in service. Sometimes a few lengths fail in service in a few weeks or months while other lengths have normal lives.

We agree with Sommerman that service performance is the all-important consideration. The aging test is the only known method of determining the performance in a shortened time. We have endeavored also to obtain all available information from auxiliary tests and service.

As emphasized by Malti, deterioration and failure in these tests resulted primarily from ionization, and this has been the weakness in insulation that has caused service failures in our 66-kv cables made in 1927 and later. We do not consider the test results proof, however, that breakdown by thermal instability is impossible. In one series of aging tests at $1^1/_2$ times normal voltage, 66-kv cables were immersed in oil. One 1926 cable deteriorated until its power factor at 70 degrees centigrade was 0.23 and then it remained stable for over 2 weeks. When the cables were removed from the oil, this cable soon failed in test. Apparently the failure was due to a pyroelectric effect which could not develop while the oil was conducting the heat away from the cable. It appears that failure can develop by ionization or by thermal instability and that increasing the voltage to accelerate the aging, hastens mainly the ionization action.

In reply to Wiseman's question, some of the joints had small standpipes in which loss of compound, if any, during the tests could be observed. When the joints were dissected, examinations were made for compound movement.

That differences in sheath expansion may have caused the differences in stabilities of samples 60 and 61 appears to be supported by the results of measurements of the gaps between insulation and sheath measured after the aging tests. These gaps were about 0.003 inch in sample 60 and 0.012 to 0.021 inch in sample 61. In general, however, no consistent relation was found between the sheath expansion and stability.

In these tests sheath temperatures were observed by means of thermocouples and by means of 2 stripes of heat-sensitive paint applied over the entire lengths of all samples. Information of this kind has been found to be helpful, but in all cases approaching failures were predicted by increases in power factor of the cable samples.

Concerning the suggestion that voltage and load cycles need not necessarily be applied simultaneously, failures have in some cases developed during the cooling period of our aging tests. Ionization effects are most pronounced during cooling when the greatest internal vacuum exists. In time after cooling, improvement in ionization factor and decrease in vacuum takes place. It appears important, therefore, that the voltage be on during the load cycles which simulates service conditions.

The theory that failure in class-*B* cable should start at the sheath does not agree with the test results. In 2 cables of class *B* failure started at the sheath while in three cables of this class failure started at the conductor.

We agree that the ionizable voids in cable insulation should be at a minimum. In cable of the ordinary type, however, some voids appear to be inevitable and therefore it is important that the compound be able to withstand bombardment at least to some extent.

Electronic Transient Visualizers

Discussion and author's closure of a paper by Herbert J. Reich published in the December 1936 issue, pages 1314–18, and presented for oral discussion at the selected subjects session of the winter convention, New York, N. Y., January 25, 1937.

N. Rohats (General Electric Company, Schenectady, N. Y.): This paper presents some very interesting work on circuits for use with the cathode-ray oscillograph. The idea of repeating a transient in exact co-ordination with the oscillograph time axis so that a standing wave on the fluorescent screen is available for visual observation or permanent photographic records has already been used in a number of prac-

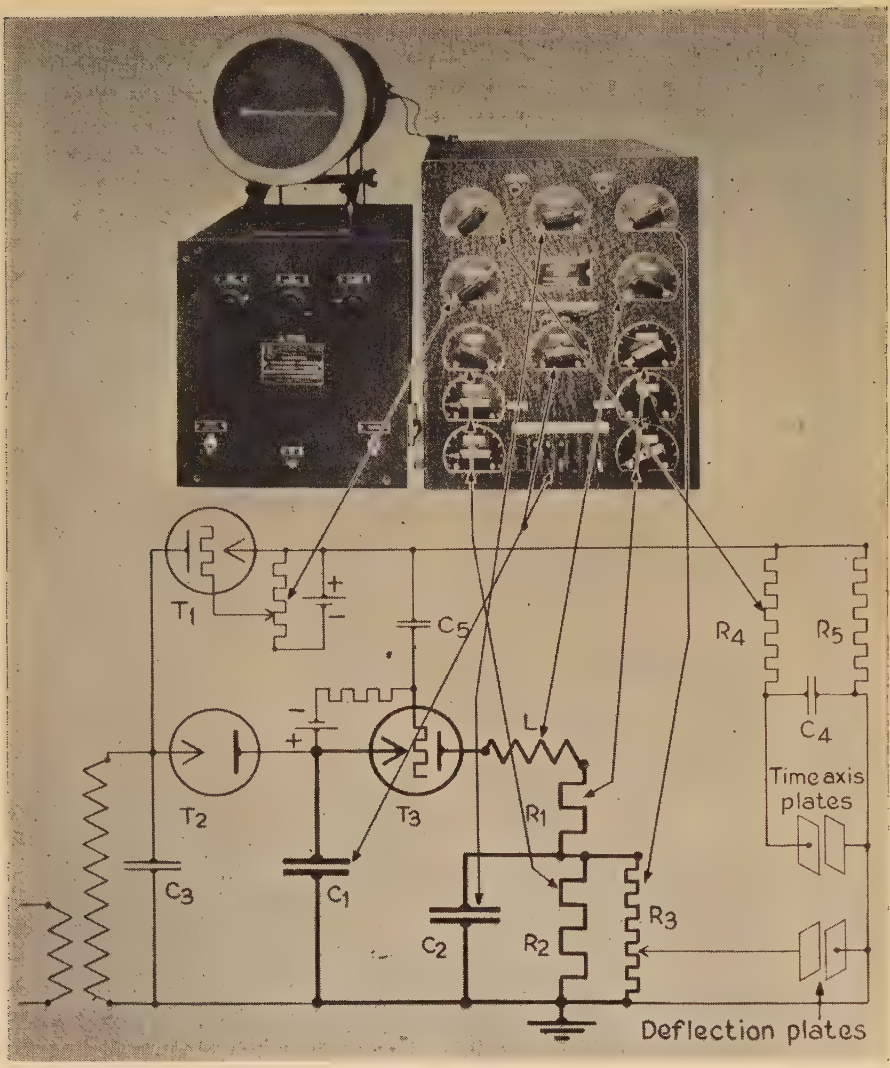


Figure 1

tical commercial applications. As the author points out, an arrangement which accomplishes this by mechanical switches has serious limitations for all but slow transients. Considerable objection may be found to the author's statement (quotation) "The device should not possess inductance, capacitance, or resistance—and this requirement prohibits the use of devices in which a capacitor or inductor charge or discharge is inherently associated with the action of that part of the switching device through which the transient flows" (quotation closed). The circuit arrangement which has been found most useful in general engineering work is one wherein the transient energy is originally stored in a capacitor and then released through a mercury-vapor tube to flow into an inductance and resistance discharge circuit. Presumably, this does not meet the author's requirements that the visualizer should be an ideal switching device. This requirement considered in the light of every day testing problems in transient work seems to have very little practical significance.

A more realistic general requirement is that such a device be capable of generating and imposing on circuits and machines, definite waves of a wide range of shapes. This requirement is met by the oscillograph electric-transient analyzer. The circuit arrangement is shown in figure 1. The complete analyzer consists of a set of variable capacitors, inductors, and resistors, a sweep circuit for a cathode-ray oscillograph time axis and the required means for properly co-ordinating these 2 so that a standing wave is visible on the oscillograph screen. Such a device from a testing standpoint is definitely related, as to type and use, to surge or impulse generators. When connections are arranged to give one output surge for each cycle of a power frequency supply voltage, it becomes a repeating type surge generator. It differs from the usual surge generator only in that it is low in voltage (1,000 volts), has a tube in place of the usual sphere gap, and is portable.

The miniature impulse generator is shown in figure 1 in heavy lines. Operation proceeds as follows: On the negative half cycle of the supply transformer C_1 receives a negative charge through rectifier T_2. On the positive half-cycle T_1 begins to conduct at the crest voltage, thereby sweeping the beam of the oscillograph at a speed determined by R_4 and C_4. The grid of tube T_3 receives an impulse through C_5 at the start of the sweep and becomes conducting thereby initiating the discharge of C_1 through L, R_1, R_2, R_3, and C_2 and producing the required wave shape across C_2.

The practical usefulness of such a device in the field of impulse testing is apparent. Many of the tests previously made with the single-discharge surge generator are now performed with a great saving in time over the old method.

For instance, in the adjustment of circuit constants of high-voltage surge generators to give standard waves such as the 1x5 or $1^1/_2$x40 for commerical impulse tests, such as for transformers, the analyzer is connected directly to the transformer and the circuit elements adjusted until the required wave is obtained on the oscillograph screen. The numerical values of circuit constants required are read from the dials of the analyzer and the high-voltage surge generator circuit constants set to correspond. This saves many hours of work.

The distribution of voltage across windings of transformers and generators is readily determined by applying output surges of the analyzer to one end of the winding and recording wave shapes at several tap points. This is a very important application because maximum surge-voltage strength is obtained only when the design is such as to cause uniform surge voltage distribution from one end of the winding to the other.

By connecting the output surges to a circuit or to machine windings and studying voltage and current reflection conditions for a range of values of resistance at the terminal end the surge impedance can be readily obtained.

These are all practical applications which have been made in many instances and through which valuable design and test information has been obtained.

Other uses such as demonstration of transient phenomena, study of induced voltages, and location of faults in circuits and windings are also of importance.

Returning to consideration of the visualizer and keeping in mind its conception as purely a switching device, it seems to be limited to special applications, particularly demonstrations of transients associated with switching phenomenon. Would the author comment on the limitation of current by the gas discharge tube itself? Also, does not the tube current controlled by the grid potential affect the shape of the transient? Also, does not tube voltage vary with current sufficiently to depart from a true switching device and to affect voltage distribution in the circuit?

The author is to be commended on the progress made in the design of visualizer circuits. It is hoped that his work will continue as the field is considerably unexplored and new factors of usefulness are quite certain to be obtained.

H. J. Reich: In discussing the limitation of my circuits to special applications Mr. Rohats seems to confine himself to the types of visualizer shown in figures 4 and 7 of my paper. This criticism also applies, however, to my circuits of figures 11 and 12 and to his own. Is it not generally true that the best instruments must be designed for specific fields of application?

I believe that the questions regarding the limitation of current by the tube and the effect of grid voltage upon the transient have been answered in my paper (paragraph 3, page 1314; paragraph 2, page 1317). So far as I have been able to determine, these factors do not affect the form of the transient.

In the type of visualizer shown in figure 7 the variation of anode voltage of an 885 gas-discharge tube affects the form of a starting transient to a certain extent when the supply voltage is low. The anode-voltage *vs.* anode-current curves of individual 885 tubes differ and are likely to change somewhat with tube age. The voltage of a typical tube falls from $17^1/_2$ volts to 17 volts in the range from 40 to 6 milliamperes; at $1^1/_2$ milliamperes it is 16 volts, and below $1^1/_2$ milliamperes it falls to zero nearly linearly with current. A discontinuity of a volt or a volt and a half, accompanied by a change in the form of the discharge may occur at about 25 or 30 milliamperes, but its effect has not been observed in the transients, probably because of the rapidity with which the current changes during the transient. Distortion decreases with increase of supply voltage and with increase of average current. With a 45-volt supply and an average current of 40 milliamperes, the distortion is small. The distortion which results from the rapid fall of voltage below $1^1/_2$ milliamperes can be prevented in most studies by shunting the transient circuit with a resistance of such size that the current does not fall below 5 or 6 milliamperes during the life of the transient. In the work referred to in reference 4 of my paper, Mr. Bennett showed that circuit parameters could be determined with considerable accuracy from oscillograms obtained with a transient visualizer of the type shown in figure 4 of my paper, using thyratrons. When transients are initiated by the interruption of current the tube does not conduct during the life of the transient and so cannot affect the form except as the result of its small inter-electrode capacitance. If the life of the transient is extremely short, some distortion may result from the finite deionization time of the tube, but this may be safely neglected in the study of transients whose life exceeds 1,000 microseconds.

Mr. Rohats' circuit is beautiful in its simplicity. It should prove to be valuable in many applications.

An Electronic Regulator for D-C Generators

Discussion and author's closure of a paper by F. H. Gulliksen published in the August 1936 issue, pages 873–5, and presented for oral discussion at the electronics session of the winter convention, New York, N. Y., January 27, 1937.

B. G. Ballard (National Research Council, Ottawa, Ont., Canada): Those of us who have requested prices from manufacturers for electronic regulators will appreciate the development of a unit which sells at a price comparable to that of electromagnetic regulators.

The regulator described in Mr. Gulliksen's paper appears to possess particularly desirable features. It has dispensed with the amplifier usually employed and it apparently does not require a specially wound field. If a constant a-c input is assumed a sensitivity of 0.1 per cent is claimed which is equal to that of any precision regulator of which I am aware. In view of these desirable features I have been wondering if it would not be possible to adapt this regulator to a-c generators. It would seem feasible to heat the cathode of the diode with alternating current and feed the resistance in series with the cathode from a small filtered rectifier with a relatively short time constant. Since the alternating current supplied to the thyratrons should now be constant the over-all sensitivity of the unit should approach 0.1 per cent. I should appreciate the author's comments on this point and also I would like to know if the diode was specially developed for this application. Is it provided with a tungsten filament or a coated filament?

Russell Ranson (Duke University, Durham, N. C.): It is understood from Mr. Gulliksen's paper that the compensating or compounding rheostat in the filament circuit of the diode must be adjusted to suit the needs of the particular generator with which the regulator is used. This adjustment is similar to the adjustment of a diverter which is used in parallel with the series field of a compound generator to give flat compounding. It follows that a different adjustment of this rheostat is necessary for every voltage for which the regulator is set by the voltage-adjusting rheostat. This means that in order to change the regulated voltage from one value to another 2 adjustments must be made.

According to Mr. Gulliksen's curves the generator voltage varies in a straight line from no load to full load, either with or without the regulator. If this be true, why not pass the generator load current through a very low resistance similar to an ammeter shunt and impress the voltage drop across this resistor on the grid circuit to obtain the necessary phase shift? This will eliminate one electron tube, the diode. It is generally believed that a reduction in the number of electron tubes is desirable. Again referring to the curves given, the voltage change as given by the diode might be equaled by a voltage drop across a very low resistance as suggested with a loss of power that will be negligible.

Even if this plan were followed, it would still be necessary to provide adjustable resistors to match the generator characteristics and to provide for generator voltage adjustment.

F. H. Gulliksen: Mr. Ranson raises the question whether it is necessary to change the compensating adjustment if the regulated voltage is varied. Theoretically this assumption is correct, i.e., if the regulated voltage is varied the regulator will not have a flat characteristic from no load to full load, but the variation in regulated voltage will be so small (approximately $\pm ^1/_{10}$ of one per cent or less) that it will not be necessary to change the compensating adjustment. This is apparent from the curves B in figure 6 and 7 which show the regulator characteristic without compensation giving a drooping characteristic of 3 per cent and one per cent, respectively. If the characteristic in figure 6 is used it is apparent that the compensating adjustment may be varied 10 per cent without giving more than 0.3 volt error in regulated voltage from no load to full load. This is well within the guaranteed sensitivity of the regulator which is ± 0.5 volts.

Mr. Ranson's suggestion to eliminate the diode may not be practicable because in that case voltage E_2 must be reduced considerably in order to obtain sufficient regulator sensitivity. If this be done the regulated voltage will vary with the changing grid-voltage characteristics of the arc discharge tubes caused primarily by varying tube temperatures.

In reply to Mr. Ballard's question, the author wishes to state that regulators for a-c generators operating on a somewhat similar principle are commercially available. In a-c generator applications a d-c exciter is usually needed and for this reason anti-hunting means must be added to the regulator circuits to obtain stable operation. The diode was specially developed for this application, and is equipped with a tungsten filament.

Sealed-Off Ignitrons for Welding Control

Discussion and authors' closures of a paper by David Packard and J. H. Hutchings published in the January 1937 issue, pages 37–40, and presented for oral discussion at the electronics session of the winter convention, New York, N. Y., January 27, 1937.

Bela Gati (Katona Rail Welding Concern, Mount Vernon, N. Y.): Three little questions: Have you tried to weld nickel with aluminum? If so, did you preheat the nickel? Aluminum melts at 659 centigrades (Celsius), nickel at 1,452. Did you use your ignitron in rail-welding process?

J. H. Cox (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): The authors have done a creditable piece of work in working out to a satisfactory conclusion, the numerous problems involved in manufacturing a sealed-off metal tube for use with a mercury arc. The paper could have been made more valuable by a discussion of the degassing processes essential in this type of device.

Limiting temperatures of 50 to 125 degrees centigrade are given. Our work indicates that the minimum temperature for satisfactory operation is a great deal less than 50 degrees centigrade, and a maximum of 125 degrees centigrade sounds impracticably high for a water-cooled device. Possibly Fahrenheit degrees were intended.

Unless more water is used than is usually necessary, a water jacket design results in a low water velocity, deposit of sediment and inefficient cooling. Cooling coils permit more flexibility in design and, for the above reasons, may supersede the jacket.

This paper provides additional confirmation of the contention made by Dällenbach several years ago, that it is impossible to build a sealed-off metal tube with a corrosive cooling system, since corrosion of iron in water produces hydrogen ions which diffuse through steel walls.

The authors mention peak currents of 7,000 amperes and 250-ampere average currents at lower peaks. I would like to ask

what average currents they are able to carry with 7,000 ampere peaks, and how large the tubes are that carry these currents.

I think that the list of advantages given is misleading, since most of them are characteristics of ignitrons in general and not limited to sealed-off designs. In general, there is an economic division between the field for sealed off tubes and continuously pumped tubes. At the lower ratings, the tube cost is low and the assembly does not justify the expense of a vacuum pumping equipment. At the higher ratings, the replacement cost of tubes would be prohibitive and the cost of a pumping set a small percentage of the total. The dividing point will be influenced by what proves to be the average life of the sealed-off tubes in service. It is quite likely that it will be greater than we are used to in the case of thermionic cathode tubes.

W. C. White (General Electric Company, Schenectady, N. Y.): In connection with the life of this form of ignitron, it is important to differentiate clearly between elapsed time and actual operating time. Unlike a tube with a thermionic cathode, it is absolutely as "dead" as an insulating bushing when not actually passing current. This is particularly true of these sealed-off tubes incorporating only one anode, as there is no holding arc or pump in operation. In normal industrial welding operating schedules, the tubes are actually "alive" only a relatively small part of the elapsed time. It is believed, therefore, that in this service tube failures will be from accidental causes traceable to use or manufacture rather than any normal deterioration factor in the ignitor or other parts of the tube.

As regards choice between sealed-off and pumped ignitrons, there is an additional factor. This is the number of years assumed for the write-off period of the investment in the welding equipment as a whole. In the resistance welding field, it is relatively short compared with, for instance, the central-station field. A short write-off period, in combination with the aforementioned intermittent operation, is favorable to the sealed-off tube. Another favorable factor is the inherent feature of this type of tube to be ready to operate the instant power is applied regardless of the time it may have been shut down.

R. E. Hellmund (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): In addition to the previously mentioned advantages of the ignitron over other types of tubes for welding purposes, it has the further advantage that it can be built either "sealed off" or for operation in connection with pumps; this, of course, would not be practicable with gas-filled tubes. The question as to which way the ignitron should be built is then purely an economical one. The sealed-off tube has a somewhat limited life, which means either complete replacement from time to time or retreatment of the tubes. This maintenance cost has to be weighed against the carrying charges resulting from the higher initial cost of tubes designed for operating with pumps. It is at once evident that the smallest tubes mentioned in the paper will prove more economical as sealed-off tubes. It is also quite certain that the very large and high-power tube arrangements will be more economical under present-day conditions if equipped with pumps. Somewhere between these 2 extremes there is a dividing line, above which the one arrangement will prove more economical and below which the other will work out best. It will probably be some time before the dividing line can be definitely determined, and furthermore, as the design, manufacturing practice and treatment of the sealed-off tubes are improved, the dividing line may shift to a higher level. However, in order to establish even a preliminary dividing line, it will be necessary to know something about the life to be expected from the sealed-off tubes in their present state of perfection. While I appreciate that it is rather early to raise this question, it would be of assistance if the authors could give an approximate idea of the life of the larger sealed-off tubes having stainless steel walls, as described in the papers.

It is very gratifying to note that in the papers presented and the discussions relating to them, the same nomenclature was used for the various tubes mentioned. After the igniter principle had been discovered in the Westinghouse Research Laboratories and practical tubes had been designed, it was of course necessary to find a fitting designation for these tubes. The name "ignitron," signifying an igniting device, was chosen, and in accordance with the established practice, trademark rights were secured. While this is a perfectly legitimate commercial practice, it became more and more evident as time went on that such practice was resulting in great confusion in the establishment and application of a proper nomenclature for electronic devices. Therefore, at the suggestion of the General Electric Company, the interested manufacturers relinquished their trademark rights, thus permitting anybody to refer, for instance, to the gas- or vapor-filled, hot-cathode, grid-controlled tube as the "thyratron" or to call the pool-type tube with an igniter an "ignitron."

In talking about the life of tubes, from an engineering point of view it is of course logical to express this in the number of operations or load cycles performed by the tube. On the other hand, the purchaser of welding equipment in choosing between the pumped and sealed-off arrangement, is accustomed to calculate his carrying, maintenance, and replacement charges on an annual basis for his particular application. It may, therefore, be necessary for manufacturers eventually to determine the life of tubes for a number of selected and typical types of service on an annual basis. While in the previous part of my discussion reference was made to a dividing line between different ratings, it is quite possible that over a certain range of ratings the sealed-off tube may prove more economical for relatively light and infrequent service, and pumped tubes of the same rating may be preferable for continuous and heavy service.

David Packard: The question of where to draw the dividing line between the application of sealed-off tubes and continuously pumped tanks is one which cannot be answered definitely at this early stage of ignitron use. As was brought out in the discussion, there is no question but that the smaller tubes have the field to themselves, and as we pointed out in the paper we have not yet encountered an application which required higher welding currents or greater duty cycle than can be handled by the largest sealed-off tubes now developed. If it appears undesirable to make sealed-off tubes for higher currents, there is, of course, the possibility of going to higher voltages in which case tubes of essentially the same size might be extended to higher power.

The life which will be obtained from tubes now in the field will also be an important consideration in determining how much further sealed-off tubes may be extended. In the development of the sealed-off tubes we have had every indication that they will give very long service. Our experience with tubes in the field has substantiated this belief although they have not been in use long enough to determine just what the life will actually be. There have been failures, of course, but in general the failures have been traceable to either misuse or to manufacturing defects which have showed up when the tubes were first put into service or shortly thereafter. To state a typical case; one user of the water-cooled ignitrons with 50 tubes in service under severe conditions has been operating about 7 months with no failures other than manufacturing defects which became apparent due to transportation or when the tubes were first installed. Some of the smaller tubes have been installed for approximately 2 years. Although the life of the sealed-off tubes has been entirely satisfactory thus far, the users of the tubes are protected against excessive cost in 2 ways. In the first place, the tubes are supplied on a policy which assures the user that the tube cost per month will not exceed a certain maximum amount when the tubes are used within the specified ratings. In the second place, losses which might result from a shut-down in a production line because of tube failure are kept at a minimum with sealed-off ignitrons because they can be replaced quickly and are ready for service instantly.

In closing, it might be of interest to know how many sealed-off tubes are in the field. The total number of tubes now in service is about 500. Of these about 150 are water-cooled metal ignitrons, some of which have been in service nearly a year. The remainder are the air-cooled tubes, and some of these have been in service about 2 years.

J. H. Hutchings: In regard to the temperature range in which ignitrons will operate, work done by the authors and their associates has netted results in agreement with those expressed by Mr. J. H. Cox. As Mr. Cox points out, ignitrons are able to operate at quite low temperatures (far below 50 degrees centigrade). Reasonably reliable operation has been obtained, in fact, with tubes so thoroughly chilled as to solidify the mercury. The absence (for all practical purposes) of any minimum operating temperature limit for ignitrons is attributed to the fact that evaporation of mercury from the cathode spot supplies the vapor pressure necessary for conduction of the arc current.

The limiting temperature range of 50 to 125 degrees centigrade mentioned in the paper is a range of maximum temperatures for the 6 tubes under consideration, the variation being due mainly to circuit con-

ditions. Fifty degrees centigrade applies as a maximum where high voltage and peak current are encountered and the period of current conduction is of long duration. Some air-cooled tubes will operate reliably at 125 degrees centigrade when voltage and current are low and the conduction period short.

Mr. Cox asks how large a sealed-off ignitron is required to pass peak currents of 7,000 amperes and what average current can be conducted at this peak. Size: $5^1/_2$ inches in diameter. Average current rating: 110 amperes at 550 volts, 160 amperes at 220 volts.

In answer to Mr. Bela Gati's 3 questions, we have never attempted to weld nickel to aluminum. Stainless steel and aluminum, however, have been welded satisfactorily, in which case it was not necessary to preheat the stainless steel. We are not familiar with any attempt to use ignitrons in rail-welding processes.

The matter of tube life has been discussed by others. However, Mr. Hellmund inquires into life of tubes "having stainless steel walls" and so brings the thought that a limiting factor in tube life may be gas accumulation through the process of hydrogen diffusion. Preliminary tests recently completed indicate that many years would be required for vacuum to be impaired through this mechanism.

Watt-Hour Meter Bearings

Discussion of a paper by I. F. Kinnard and J. H. Goss published in the January 1937 issue, pages 129–37, and presented for oral discussion at the instruments and measurements session of the winter convention, New York, N. Y., January 28, 1937.

H. B. Brooks: See discussion, page 880.

Stanley Green (Duncan Electric Manufacturing Co., Lafayette, Ind.): In this paper a great deal of work has been summarized leading toward a better watt-hour-meter bearing. The demand for such a bearing which will last up to 20 years without replacement under the recently imposed conditions of outdoor operation with attendant variations in humidity and temperature has been insistent. The bearing problem certainly is one of the most acute of any in the watt-hour-meter art today. During the past few years I have followed with interest and some concern the work outlined in much of the bibliography appended to this paper and also want to commend the authors on their industry and thoroughness with respect to the material in the paper.

Personally, however, I feel that we shall not attain the object of our search until oil is totally eliminated in bearings. Alloys must be obtained which will run on a jewel dry without being harmed. With the development in the field of alloys progressing as it is, I feel that there is more possibility along this line than that a perfect oil will ever be developed. Even if a perfect oil were available, there are still operating inconveniences and uncertainties attached to its use.

A. R. Rutter (Westinghouse Electric & Manufacturing Company, Newark, N. J.): The authors have prepared an excellent paper which will be used by meter engineers as a reference on the subject of meter bearings. While most of the data deals with the pivot type of bearing, the ball type is mentioned a number of times in the paper. Some additional information on the ball bearing might be of interest to anyone studying the problem.

The ball type of meter bearing has been manufactured in America for over 35 years, during which time a large percentage of the meters manufactured have been equipped with this type of bearing. The functioning of the ball bearing is described in Mr. Lenehan's article in the November 1929 *Electric Journal*.

The performance of the ball bearing has been recognized by the utility companies because of 3 important fundamentals. These are:

1. Sustained meter accuracy
2. Long life without lubrication trouble and wear
3. Low maintenance cost

The ball bearing satisfies these outstanding characteristics because the ball turns between 2 jewels and acts as an infinite number of pivots, with the result that the wear of the parts is distributed over the entire surface of the ball and over a large portion of the jewel area. Since a double jewel is used and the ball rolls in the jewels, the jewel surface used is much greater than in the pivot bearing. For all practical purposes the ball has a rolling action and does not require lubrication. The action of the ball bearing is such that dirt does not interfere seriously with the bearing.

The radius of the ball used in American meters is 0.031 of an inch. The data in the paper, particularly figures 3, 4, and 12, confirm the reason for the very good results in service that have been obtained with the ball type of bearing.

A large amount of study has been given to the question of material for the ball, but, to date, no commercial materials have been accepted and approved as being superior to carbon steel.

A. J. Allen (Consolidated Edison Company of New York, Inc., New York, N. Y.): The paper "Watt-Hour Meter Bearings," by I. F. Kinnard and J. H. Goss is very commendable as it indicates an endeavor toward an end that is very much desired by meter engineers.

For a long period of years watt-hour meter lower bearings have consisted of natural or synthetic sapphire jewels with glass-hard steel pivots or balls. The use of steel in meter bearings has proved undesirable because if the steel rusts rapid failure of the bearing follows: Rust or ferrous oxide is most abrasive and forms readily unless some protective coating is maintained: for this purpose oil has been used. The oil also provided lubrication which is necessary for steel pivots but not for steel balls; in fact its presence in a ball bearing is undesirable from a lubrication standpoint.

The need to find or develop a substitute for high-carbon steel that would not form an abrasive oxide has been foremost in the minds of meter engineers and at their urgent request several meter manufacturers have given the development serious attention. The increasing practice to install watt-hour meters on the outside of buildings further intensifies the need, and it injects into the problem temperature range requirements for bearing lubricants not necessary for meters installed indoors. There is a well substantiated belief that oil is not necessary or desirable in a meter bearing. The authors state "the provision of a good lubricant is not a simple matter," this has been true ever since the first oil was placed in a meter bearing. The sad experience which followed the use of fish, vegetable and mineral oils and various oil compounds has well established the hope to eliminate the need for oil in meter bearings. As to this, the authors hold out a ray of hope when they state "While all tests definitely show that proper lubrication increased the life of bearings, it has also been shown that cobalt-tungsten performs exceptionally well even without oil."

Table I—"Properties of Pivot Materials" indicates in the second column whether the materials were corrosive or not. Cobalt-tungsten is shown as not being corrosive yet it oxidizes when exposed to air. If the oxide is nonabrasive that fact is naturally the most important. Beryllium alloys, as indicated in the table, may have some possibilities. I have experimented with a beryllium-nickel-copper alloy that has proved superior to beryllium alloyed with nickel or copper alone in respect to non-abrasive oxide.

The matter of shock resistance of pivot materials is most important. It appears that reducing the contact area to an area as small as possible has been responsible for considerable damage to jewels. The advantage of a larger area is apparent from the tests made in comparison with steel and cobalt-tungsten pivots. It appears that a cobalt-tungsten pivot should have a contact area equal to that created by the shock of the short-circuit test on the assumption that a short-circuit shock would not cause deformation of a pivot having this area.

Accelerated life tests, while necessary, do not prove entirely the serviceability of a material, they do, however, indicate a trend that can be expected. A meter bearing that has a life of 20 years and does not require oil is not far away.

Amplification Loci of Resistance-Capacitance Coupled Amplifiers

Discussion and author's closure of a paper by Anatoli C. Seletzky published in the December 1936 issue, pages 1364–71, and presented for oral discussion at the electronics session of the winter convention, New York, N. Y., January 27, 1937.

Dale Pollack (nonmember; RCA Manufacturing Company, Inc., Camden, N. J.): In the form in which the author writes the vector amplification of a resistance-coupled amplifier, (2) of his paper, it appears that the locus is not a single circle, but is the vector sum of 2 different circles. However, the equation is easily manipulated to show

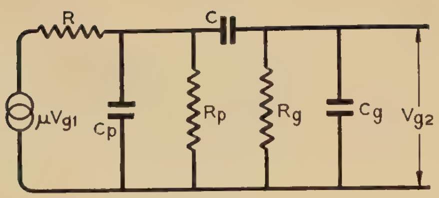


Figure 1

that it may, in fact, be represented by the locus of a single circle, and that the author's 2-circle representation is unnecessarily complicated. Consider the author's (2),

$$A = \frac{-jK\omega}{\omega^2 - jb\omega - c} \tag{2}$$

dividing through by the numerator gives

$$A = \frac{1}{\frac{1}{k}\left[b + j\left(\omega - \frac{c}{\omega}\right)\right]}$$

Making the substitution

$$m = \omega - \frac{c}{\omega}$$

yields

$$A = \frac{1}{\frac{1}{k}(b + jm)} \tag{2a}$$

where m is now the parameter instead of ω. (2*a*) is the locus of a single circle, which is evident by comparison with the author's (4), or from the following:

$$\frac{1}{A} = \frac{1}{k}(b + jm) = \frac{1}{|A|}\epsilon^{j\theta} \tag{2b}$$

then

$$\frac{1}{|A|} = \frac{1}{k}\sqrt{b^2 + m^2} \tag{2c}$$

and

$$\frac{m}{b} = \tan\theta \tag{2d}$$

Substituting (2*d*) into (2*c*)

$$\frac{1}{|A|} = \frac{b}{k}\sqrt{1 + \tan^2\theta} = \frac{b}{k}\sec\theta$$

and, inverting,

$$|A| = \frac{k}{b}\cos\theta \tag{2e}$$

(2*e*) is the polar equation of a circle passing through the origin with its center on the horizontal axis.

This same conclusion is reached by Luck in his paper "A Simplified General Method for Resistance-Capacity Coupled Amplifier Design," IRE *Proceedings*, volume 20, page 1401, 1932, when he states, on page 1403, ". . . there is a simple fixed relation between gain magnitude per stage and phase displacement per stage, the former being proportional to the cosine of the latter."

The author's ingenious algebraic solution is correct, except that the resulting locus is erroneously called a bicircular quartic instead of simply a circle. By starting with this single circle, instead of taking the sum of 2 circles as the author does, the computation is simplified. The writer has been using a graphical design method based upon the simple circular locus, and it may be of interest to present it. Using Luck's notation and analysis (see figure 1) which differ slightly from the author's,

let

$$\frac{1}{R_s} = \frac{1}{R} + \frac{1}{R_p} + \frac{1}{R_g}$$

$$\frac{1}{R_l} = \frac{1}{R} + \frac{1}{R_p}$$

$$w = \left(1 + \frac{C_g}{C}\right)\sqrt{\frac{R_g R_l C}{R_s^2\left(C_p + C_g + \frac{C_p C_g}{C}\right)}}$$

then

$$A_0 = \frac{S_m/R_s}{1 + C_g/C}$$

is the maximum gain occurring at a frequency f_0

$$f_0 = \frac{1}{2\pi\sqrt{R_l/R_g(C_pC + C_gC + C_pC_g)}}$$

S_m is the mutual conductance of the tube. Also let

$$y = \frac{f}{f_0} - \frac{f_0}{f}$$

be the frequency parameter. Then

$$|A| = A_0\cos\left[\tan^{-1}\frac{y}{w}\right]$$

where

$$\phi = \tan^{-1}\frac{y}{w}$$

is the phase angle of the vector amplification. The only assumption made, aside from those from linearity and freedom from feed-back, is that

$$\frac{C_p - C_g}{C} << 1$$

This assumption does not affect the shape of the amplification locus but it does simplify some of the equations.

The general locus for any resistance-capacitance amplifier may now be sketched by drawing the circle on polar-co-ordinate paper, as in figure 2. By plotting the frequency determining parameter y/w linearly along the vertical line, as shown, and projecting from the origin through the vertical line to the circle the frequency determining points on the circle are found. Knowing the constants of the amplifier, its gain and phase shift can be found very rapidly with the aid of the circle diagram. It is only necessary to calculate w and y for the desired frequencies from which the value of the vector gain may be read from the diagram. The converse process, for obtaining the circuit constants from a known frequency and phase characteristic, may also be carried out. The process is very similar to the one suggested by Luck, except that the circular locus on polar paper replaces Luck's generalized gain and phase curves. This reduces the labor involved and improves the accuracy of the method.

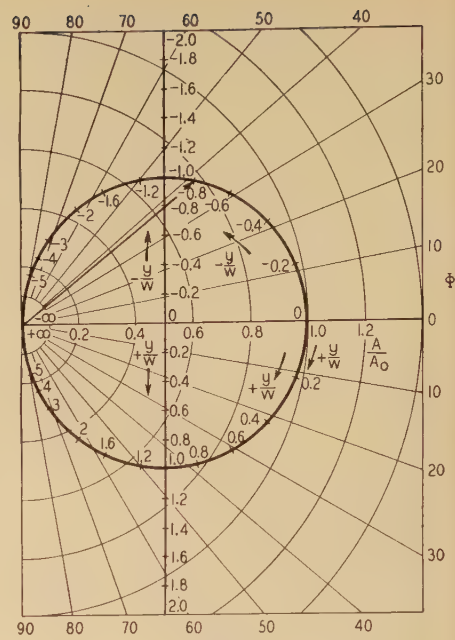


Figure 2

I. Rotkin (United Transformer Corporation, New York, N. Y.): This paper presents an interesting and convenient solution of the problem of calculating the complex response of a resistance-coupled amplifier from its circuit constants.

To the extent that grid-to-plate capacity in the vacuum tube is neglected the final result is, however, only an approximation. This is the case even in what Mr. Seletzky calls the exact equivalent circuit. The amount of error introduced by omitting consideration of the grid-to-plate capacity depends on the circuit constants, and it increases with frequency. There are 3 discrepancies introduced by this approximation.

When the grid-to-plate capacity is taken into account, the exact equivalent circuit of a resistance-capacitance stage of amplification becomes like the circuit of figure 3, where C_{gp} is the grid-to-plate capacity of the amplifier tube, and R_g' and C_g' are, respectively, the effective input resistance and input capacity of the following tube. The other symbols are the same as those in the paper.

Except for very high frequencies $R_p\omega C_{gp}$ is much smaller than μ. Hence the error introduced by neglecting the imaginary term, as the author has done, is negligible.

Very small, though not in general negligible, is the error introduced in the paper by neglecting the C_{gp} term in the output capacity.

The third error is the most serious. It may be so large as to limit the author's method to the low audio frequencies for certain types of tubes. Mr. Seletzky assumes the input impedance of the following tube to be constant and to consist of the grid resistor and grid-to-cathode capacity of the following tube. Under actual condi-

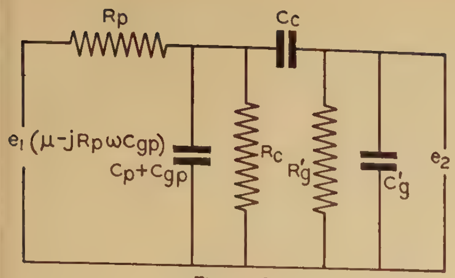


Figure 3

tions, however, the plate circuit of this tube is reflected back into its grid circuit through its grid-to-plate capacity. As a result the values of R_g' and C_g' vary with frequency.

I have calculated this effect for 2 types of tubes, the 6*F*5 high-mu triode and the 6*J*7 pentode, both of which are very commonly used in resistance-capacitance coupled amplifiers. A 6*F*5, with a one-megohm grid resistor, a 250,000-ohm plate-loading resistor, and total grid-to-cathode and plate-to-cathode capacities of 20 micromicrofarads including socket terminals and wiring, when used at 8,000 cycles, will have an effective input resistance of only 155,000 ohms and an effective input capacity of 162 micromicrofarads. In short, the effective input resistance is only 15.5 per cent of the one-megohm grid resistor, while the effective input capacity is 800 per cent of the grid-to-cathode capacity. At higher frequencies the error is even larger.

Even the 6*J*7, which has an extremely small grid-to-plate capacity (only 0.005 micromicrofarads), gives effective values of R_g' and C_g', respectively, of 0.99 megohm and 21.2 micromicrofarads. This represents an error of one per cent in resistance and 6 per cent in capacity. Here, too, the error would be greater for higher frequencies.

Mr. Seletzky's method is, nevertheless, a very valuable one. If care is used in its application, it should yield results of sufficient accuracy for most purposes with a minimum of effort. It will be especially useful in problems which involve phase shift.

A. C. Seletzky: Mr. Pollack in his discussion brings out several valuable comments on the design of resistance-capacitance coupled amplifiers. It should be noted, however, that throughout the entire paper, the angular velocity ω_1 is treated as the scalar variable. *With respect to the scalar variable* ω the general equation for amplification as given by (2) remains a bicircular quartic, because it consists of the sum of 2 circles, which sum does not reduce to the canonical expression of the circle,

$$\frac{a + b\omega}{c + d\omega}$$

inasmuch as it involves higher powers of ω, as may be seen from equation (2), namely

$$A = \frac{-jk\omega}{\omega^2 - jb\omega - c} \qquad (2)$$

In the author's opinion, the opening line of the paragraph in the paper following equation 6, "The variable scalar in the present case is the angular velocity . . . . " should make it reasonably clear that the variable scalar treated in the problem is the angular velocity.

Mr. Pollack throws the amplification equation into the form of a circle by changing the scalar variable from ω to

$\omega - c/\omega$

which is $(\omega^2 - c)/\omega$

and by this artifice considers the amplification to be circular in form. It is, but the scalar variable in the transformed equation is not the angular velocity ω, but a new function of angular velocity, involving higher powers of ω. Thus instead of using a linear scale line in units of ω, Mr. Pollack is using a linear scale line in units of

$(\omega^2 - c)/\omega$

It should be evident, therefore, that Mr. Pollack, instead of contradicting any statements made in the paper, is merely introducing a new scalar variable of higher order. Thus the general equation of amplification may be considered to be either (a) a bicircular quartic, i.e., the sum of 2 circles, each component circle having a linear scale of ω or (b) a single circle with a linear scale in units of

$(\omega^2 - c)/\omega$

Mr. Pollack's modification of Mr. Luck's method applied to the single circle is very interesting and helpful. The author is gratified in observing the increasing use of the circle diagram to eliminate time-consuming computation. It is difficult to judge as to which particular method involves the minimum of time and effort. Generally speaking, however, it has been the experience of the author, that what is eliminated from the drawing board is merely transferred to the slide rule and tables of functions, and that best results are obtained from a judicious balance of the 2.

Mr. Rotkin's comments on the variation from linearity of the general circuit are greatly appreciated. This paper was written on the basis that the "exact" equivalent circuit as shown in figure 1, was sufficiently exact to be valid for the great majority of resistance-capacitance coupled amplifiers, and Mr. Rotkin concurs with this viewpoint in the closing paragraph of his discussion. Designers encountering the somewhat special conditions described by Mr. Rotkin should be guided by his observations. The author hopes that Mr. Rotkin will formulate the proper expressions of circuit coefficients, expressed as functions of the frequency, and incorporate them into a general method of determination of amplification loci.

Development of a Modern Watt-Hour Meter

Discussion and authors' closure of a paper by I. F. Kinnard and H. E. Trekell published in the January 1937 issue, pages 172–9, and presented for oral discussion at the instruments and measurements session of the winter convention, New York, N. Y., January 28, 1937.

Stanley Green (Duncan Electric Manufacturing Co., Lafayette, Ind.): Performance of the new meter described in this paper is better than has been considered acceptable previously and the fact that it is now proposed indicates that there may be a demand for it by the utility users of meters. In general, such improved characteristics in a meter will cost more to manufacture—but not much more. The idea has been advanced by some utilities that by concentrating production in one size, this small cost increment can be overcome. Under these conditions, the low-capacity type would become rare and production would be concentrated in only 2 sizes, domestic and commercial, with the former greatly predominating. This view appears constructive and even if the future domestic meter were increased in cost slightly, the increased range could be worth it to the utilities, not only from simplification of operations but because it will give ample margin for the vitally important load building activities of the future.

The authors have accurately expressed the elementary design limitations in equations 1, 2, and 3 and the discussion relating thereto. On these, most designers should be in agreement. Unfortunately, space available has apparently not permitted a more detailed exposition of subsidiary design factors and their interrelationships, although some of these are mentioned by the authors. Relative gap lengths and proportions, pole configurations and proximity, relative flux density in interrelated parts and characteristic curves of the magnetic material entering into parts of the structure all so complicate the problem that many solutions instead of only one unique one are possible. This is where the skill and judgment of the designer are utilized and if it were not for this, there could be only one good meter design. Instead, there have always been many designs and generally each is a little better than its predecessors. A paper such as the present one is useful in a high degree as it supplies still another step in that stimulating chain of advances which is ever-lengthening because of changing requirements in the electrical industry.

The short mean length of potential-coil turn mentioned by the authors is a useful expedient. The recognition that load compensation is necessary to give linear performance at the heavy-load end of the registration curve is constructive. Better methods of controlling this form of compensation have been developing in the last few years and precision load compensation in any reasonable amount can now be obtained by several forms of compensators all working on the same "saturable bridge" principle. It has been recognized by designers for some time that the load compensator modifies the shape of the registration curve at light loads and I think we can look for continued beneficial effects from the compensator on this end of the curve in future designs.

In modifying the design of a given meter to meet the new long-range performance more than one path can be taken. It would be interesting to describe more than one avenue, but for brevity and clearness, I mention only one simple scheme:

In a paper in the October 1935, issue of Electrical Engineering, I described a new watt-hour meter which has been manufactured in 5-, 15-, and 50-ampere nominal ratings. The 3 ratings in this meter could be modified easily to duplicate the new performance now proposed. In this modification the 15-ampere rating would become

the "domestic" meter. Its torque would be raised from 46 to 62.8 by increasing the potential-element ampere-turns. This would give the same torque at 12.5 amperes as the new watt-hour meter and would, of course, allow the same light-load performance as such performance is basically a function of torque available. The increased potential excitation would be accomplished at the expense of raising the potential watts loss from 0.9 watt to about 1.25 or the same as the meter of the paper under discussion. The increased ratio of potential to current flux makes it easy to compensate the modified meter so that the performance is straight line to 400 per cent load or 60 amperes since before modification the droop at this point was only 1.5 per cent. Increasing current-coil copper and providing a stronger damping magnet are details easily accomplished.

Since a stronger damping magnet would be used, the watt-hour constant would not be changed and for the 15-ampere 2-wire "domestic" meter would be one, which is also a desirable constant for use with all types of rotating standards now in use.

H. B. Brooks (National Bureau of Standards, Washington, D. C.): The papers by Kinnard, Goss, and Trekell are gratifying examples of the modern trend away from the old policy of secrecy. If the design of electrical measuring devices is to progress as it should, designers must be allowed a reasonable degree of freedom to publish the principles which guide them, the results of their experimental studies, and the particular structures which form the end result of their work. It is to be hoped that those who control the policies to which the designing engineer must conform will discern the advantages which will accrue to all concerned as a result of such co-operation in the advancement of the art.

Referring to the analysis chart, table I of Kinnard and Trekell's paper, I suggest that it would be interesting to have for comparison the corresponding figures for the meters now being produced by the other American manufacturers. Most of the data for one of these other meters was given in Mr. Green's paper in volume 54 of the TRANSACTIONS.

The suggestion of Kinnard and Trekell that modern watt-hour meters should be rated in terms of the nominal and the maximum current rating deserves consideration with a view to general adoption. The retention of the present nominal rating (i.e., 5 amperes for a meter with a maximum continuous rating of 15 or 20 amperes) is a necessity for calibration and comparison purposes for the present and for the immediate future. The straight-line accuracy characteristics over a large portion of the load curve raises an interesting question in regard to what shall be eventually taken as the nominal test point. If individual treatment of meters were practicable, the average load of the installation would be the logical one at which tests and adjustments would be made. Since this is not feasible, and since tests of modern meters at the maximum current would require that the testers should carry larger and heavier equipment, it seems logical to adopt the present values of calibrating current for the new meters.

Table II of Kinnard and Trekell's paper does not include a meter of 2.5 amperes nominal, 7.5 amperes maximum rating. This meter would differ from the authors' "low-capacity" meter only in having 20 turns on each current pole, and would be preferable to the nominal 5-ampere meter for use in connection with current transformers. I understand that meters of 2.5 amperes nominal rating are being used for this purpose. It seems advisable to recognize this formally as a fourth standard rating.

F. C. Holtz (Sangamo Electric Company, Springfield, Ill.): The authors are to be complimented on their very clear and concise presentation of a subject which, while fairly clear to the designer of watt-hour meters, may not have been fully appreciated by the user.

By a careful and systematic analysis it has been possible to greatly extend the useful range of a meter by the introduction of various types of compensating means. In this way the manufacturer has kept pace with the increased demand of the user until now it seems possible that we may be able to further limit the number of types or capacities required for a more diversified application.

From a manufacturing standpoint, I believe we agree with the choice of ampere-turns which will simplify our problems. In doing so, however, it should be on a basis which fully rcognizes the requirements of the user as to convenience of testing and the use of testing equipment.

I doubt if the time is right for us to forget meter ratings in volts and amperes and merely refer to them as "domestic," "commercial" or other meters.

There is also some question as to the advisability of changing ampere rating from the series toward which the industry has been striving. This may be of no great importance or it may readily be modified by advancements which as in this case would definitely tend toward the elimination of one or more of the present types. The advantages in this case would lie in simplification of stocks which is a great benefit to producer and user alike.

In the present instance we may find ourselves in a dilemma. If the author's meter were to be rated at 15 amperes and given a watt-hour constant of 1.5, this would not agree as to constant with existing meters of similar manufacture. If it is given a rating of $12^1/_2$ amperes with the same constant, then the capacity is out of line with the present accepted standards. Of these 2 the choice should probably rest with the change in capacity in order that the constants may remain in line with present practice.

E. D. Kane (The Detroit Edison Company, Detroit, Mich): This paper is a worthy contribution to the art of metering, in that it presents a comprehensive discussion of the elements affecting watt-hour meter design. The watt-hour meter holds a unique position as an instrument for measuring a quantity from which revenue is derived because it is subjected to so many variable factors as a result of its operating location in the field. Also, the accuracy requirements must be more stringent than other forms of commercial measuring apparatus, with a minimum amount of attention.

Perhaps the nature of the problem and its importance has acted as an incentive for improvement in the art, so that now the most scientific methods of design and analysis are employed together with pure scientific research to determine the underlying theories of operation.

The contents of this paper graphically illustrates this fact and the treatment of analysis deserves special mention. Table I may well serve as a criterion for meter acceptance with perhaps some other constants added. Such a table allows uniform presentation of the data in a concise practical style. The determination of meter constants to establish performance characteristics might reduce the labor in making acceptance tests and reduce operating parameters to a more equal basis. Information concerning additional factors may prove desirable. Suggestions from designers as to the best parameter which could be used as a relative index of over-all performance would be interesting. No doubt such a value will be found in the future as the investigations are carried further into the problem to which this investigation has contributed so much.

It is to be hoped that the bibliography of meter research will continue to grow and the literature will be as productive of progress as that of other scientific and engineering fields.

The proposed rating discussed for new watt-hour meters appears to offer considerable advantage as is pointed out in the paper, namely;

(*a*). Reduced stock of meters and parts
(*b*). Meets field requirements to better advantage
(*c*). Offers improved standardization in test methods

The question of the test constant value of the "long range" domestic, namely; 1.5, may cause confusion but that condition can be easily overcome by proper run selection.

I. F. Kinnard and **H. E. Trekell:** Doctor Brooks has suggested that the 3 self-contained ratings be augmented by a meter of 2.5 ampere nominal current rating for use with instrument transformers. With a 5-ampere-secondary current transformer, the use of a 2.5-ampere meter provides greater insurance of accuracy of registration, especially at light loads, since the meter works at double torque. From a thermal standpoint, current transformers will not operate continuously at loads above 7.5 amperes in the secondary winding. A 2.5-ampere meter is the best choice for the actual operating range of the transformer. The burden of the current circuit of a watt-hour meter is sufficiently low that the increased burden of the 2.5-ampere meter is usually not objectionable.

Mr. Green has proposed an interesting modification of a present meter design. However, it has been found from experience that a small inherent error can be compensated much easier than a large error. Furthermore, due to variations in materials and manufacturing tolerances, attempts to compensate large, inherent errors usually result in considerable variations in the performance of the device.

As pointed out in the paper, any design

can be readily analyzed and its merit judged by a tabulation of data as shown in table I, page 178. It would be interesting, as suggested by Doctor Brooks, to give complete data of this nature for suggested alternate designs.

While it is true, as Mr. Holtz points out, that when rated in accordance with present established constants the "domestic" meter described is in reality a 12.5-ampere size, yet it might be called a 15-ampere meter. In this event, however, the relation between watt-hour constant and ampere rating is different from any established standard. If this is done in order to meet present rating classifications, the inherent, nominal full load of 12.5 amperes should also appear on the nameplate to prevent confusion.

Mr. Kane's discussion is very much to the point, and as he points out, meter design and operating constants can be rationalized and guided by scientific analysis.

Impulse-Generator Voltage Charts for Selecting Circuit Constants

Discussion and author's closure of a paper by J. L. Thomason published in the January 1937 issue, pages 183–9, and presented for oral discussion at the instruments and measurements session of the winter convention, New York, N. Y., January 28, 1937.

C. F. Harding (Purdue University, Lafayette, Ind.): This paper provides a much-needed rapid method of adequately determining and standardizing surge test results as they are undertaken in the various laboratories wherein some difficulties have been experienced in the past in securing comparable data. Demands on the part of prospective customers for surge tests to be made in independent laboratories are becoming more numerous and therefore any developments, such as are outlined in this paper, looking toward the co-ordination of results obtained from surge generators of varying capacitance and discharge constants represent a distinct contribution to the pioneer work of our profession.

In the accompanying discussion, which I shall present with my endorsement, from Mr. C. S. Sprague, who is in charge of the surge testing of our high-voltage laboratory at Purdue University, a further simplification of the standard calculations of the paper which are applicable to the frequently used $1^1/_2$x40 wave will be evident.

J. H. Hagenguth (General Electric Company, Pittsfield, Mass.): Mr. Thomason has presented a paper which should prove very useful in laboratories where impulse work is being done. Especially in those laboratories, where cathode-ray oscillographs are not available the charts and curves presented should save considerable time as compared to the more laborious methods of actual calculations to obtain accurate information of the wave shape used for a particular impulse circuit.

Where accuracy required is within ± 5 per cent of actual values some rather simple

Table I

Constant	By Test	By Chart	By Equations
K_1	0.30	0.30	0.30
K_2	0.057	0.057	0.057
Front (microseconds)	1.9	1.9	1.88
Duration (microseconds)	40	39	37.7
Crest (per cent)	72	71	73.2
K_1	0.128	0.128	0.128
K_2	0.073	0.073	0.073
Front (microseconds)	1.4	1.5	1.35
Duration (microseconds)	44	44	43.3
Crest (per cent)	81	80	82.5

equations are available as follows using the same notations as the paper:

$$\text{Wave front: } 3R_1C = 3R_1C_2\frac{1}{1 + C_2/C_1} \qquad (1)$$

$$\text{Wave duration: } 0.697(R_1 + R_2) \times (C_1 + C_2) = 0.697R_2C_1(1 + R_1/R_2) \times (1 + C_2/C_1) \qquad (2)$$

$$E/E_0 = \frac{1}{1 + R_1/R_2}\ \frac{1}{1 + C_2/C_1} \qquad (3)$$

These equations yield remarkably good results if R_1 is equal to the critical resistance as explained in the paper.

Applying these equations to the 2 examples presented the values of table I are obtained.

It can be seen that the equations give numerical values which check closely the test results and the values obtained by means of the charts. Often it is desired to have a higher crest than that obtained with the circuit of figure 2 but maintaining the same wave duration. In such a case it is an advantage to insert another resistance R_3 from the junction of C_1 and R_1 to ground. In that case the equations 1 and 3 remain unchanged, while the equation 2 changes to

$$\text{Wave tail: } 0.697R(C_1 + C_2)$$

where

$$R = \frac{(R_1 + R_2)R_3}{R_1 + R_2 + R_3} \qquad (4)$$

For transformer testing more complicated charts would have to be used to take care of the inductance to ground of the transformer. It is also relatively difficult to determine the impulse capacitance of the transformer winding, which with any additional load capacitance determines the wave front. Although these voltages, wave fronts, etc., can be calculated, it would be a rather time consuming task to do so, when a large number of transformers have to be tested. Fortunately the electrical transient analyzer is available, with which the circuit constants required for any particular transformer can be determined rapidly and accurately.

C. S. Sprague (Purdue University, Lafayette, Ind.): Although the use of charts and curves for quickly determining the impulse generator constants for producing a specified wave is not new, the author, by the use of *ratios* of circuit constants, and of wave front and duration times, presents a method whereby the circuit constants may be determined for producing practically *any* wave shape, or conversely the wave shape produced by a given set of constants may be determined.

For a wave, such as the $1^1/_2$x40, which is in sufficiently general use to warrant the procedure, the use of the curves can be considerably simplified by plotting, in figures 4*b* and 4*B*, K_1 *vs.* K_2 for the constant value of t_1/t_2 representing the $1^1/_2$x40 wave. Likewise in figures 4*a* and 4*A*, the value of C_1R_2 may be plotted against K_2 for the particular wave front time $t_1 = 1^1/_2$ microseconds. This procedure would reduce figures 4*a*, 4*A*, 4*b*, and 4*B* to a single curve each, and avoid interpolation between a family of logarithmically spaced curves on a logarithmic scale. In the more general nature of the data as presented by the author, these simplifications could not be obtained; however, it might be well to indicate the advantages to a particular laboratory of limiting the variables to those representing conditions in that laboratory.

The author indicates the growing need for specification not only of the time constants of the impulse but also of the circuit constants of the generator producing the impulse.

The above seem to be the principal contributions of this paper.

As is well known a particular wave shape can be obtained from a variety of circuit constants. However, the actual test results obtained, particularly in flashover tests of equipment having considerable time lag, will depend upon the series impedance or the rate at which energy can be supplied to the test piece. This is particularly true at short flashover times or flashover on the rising front and is a further argument for specifying, at least the permissible range, of the generator constants.

On page 185 under circuit II, the author calculates a necessary inductance of 58 microhenrys and states that if this value cannot be obtained, or if the actual $L_1 = 40$ microhenrys, that the values of R_1 and R_2 can be adjusted on a straight line basis. Will not this change the duration of the wave? Why not add 18 microhenrys to obtain the calculated value of 58 microhenrys? Theoretically the limitation on L_1 is the minimum value of the inherent self inductance of the generator circuit.

In chart II the author states (page 5) that

$$L_1 = \frac{R_1^2C}{4}$$

or in other words

$$R_1^2 = \frac{4L}{C}$$

so that oscillations of the generator inductance and the effective series capacitance cannot occur. Three values of W are denoted by asterisks as indicating real roots, presumably meaning a unidirectional impulse, which the author designates (page 6) as a "smooth wave." Are all other waves oscillatory, and if so, cannot a damped oscillatory wave be smooth? From the conditions

$$L_1 = \frac{R_1^2C}{4}$$

superimposed oscillations could not occur. Perhaps the author's definition of a "smooth wave" might clear up this point.

On page 188 a value of 1.4 microseconds is given for the wave front as determined from the oscillogram of figure 7. With the slow sweep used in figure 7 the accuracy of determination of the wave front time seems somewhat questionable.

P. L. Bellaschi (Westinghouse Electric & Manufacturing Company, Sharon, Pa.): The impulse generator came into engineering prominence about 5 years ago. At that time the basic circuits and generator characteristics when testing electrical apparatus were analyzed and carefully studied.[1] Since then the literature on the subject has grown both here and abroad.[2] Some of these contributions relate to the experience acquired, others pertain to further refinements in the analysis or method of calculation.

The present paper is of a character that should be helpful in reducing labor where charts similar to those in figure 4 may not be available. The calculation of these or similar charts is based on circuit analysis, on methods where terms are expressed as ratios between similar circuit constants and on plotting the results conveniently and effectively in terms of the time constants of the circuit—all of these having been developed and applied some 5 years ago. The usefulness of such methods is well demonstrated in the present paper.

Reference is made by Mr. Thomason that the circuit diagram of figure 2 has been recommended as basic by the International Electrotechnical Commission. This statement should not be misconstrued perhaps to the effect that this circuit represents all circuit conditions encountered in present-day testing. For example, this is not necessarily the basic circuit when testing transformers for such apparatus may introduce other elements into the circuit, such as low inductance to ground, substantial energy drain from the generator into the transformer circuit proper and also into the circuit from which the transformer may be excited at normal-frequency voltage. A consideration of the work by the IEC covered in the report in question will bring to light that this circuit representation is really intended, when such loads as insulators, gaps, bushings, and similar equipment are connected to the generator.

A good number of impulse generators have come into existence both in this country and in Europe since 1932. These generators have for the greater part been built to generate a smooth impulse voltage of a $1^1/_2$x40-microsecond duration or thereabout. When we compare for example the half-a-dozen impulse generators built hereto for 3 million volts, particularly those for testing equipment of relatively large capacitance, we find that the generator capacitance, the self-inductance, the stray capacitance, the damping resistance, and the load resistance for each generator are respectively of the same order of magnitude as the corresponding constants of the other generators. Thus in practice for a given voltage rating of the generator the part of the circuit charts, such as in figure 4 of the paper, which would be used is rather localized. Considering the various voltage ratings of generators even then only certain "practical" regions in the charts would really be used.

References

1. Characteristics of Surge Generators for Transformer Testing, P. L. Bellaschi. AIEE Transactions, volume 51, December 1932, pages 936–951.

2. In addition to the works by P. L. Bellaschi, J. L. Thomason, and C. S. Sprague presented to the AIEE, there have been contributions elsewhere in recent years by Roys (Purdue University), Lewis (Bureau of Standards), Angelini (Italy), Goodlet (England), Elsner (Germany), and others both in this country and abroad.

J. L. Thomason: In their discussions of this paper Dr. C. F. Harding, and Messrs. C. S. Sprague, J. H. Hagenguth, and P. L. Bellaschi have extended the art of impulse-voltage testing by adding new and qualifying information.

Mr. Sprague has asked for the author's definition of a smooth wave. It can be stated thus: "In impulse testing the voltage wave applied to the test piece will be considered smooth and when its mathematical expression for a circuit of five constants (figure 2 in paper) takes the form

$$e = A\epsilon^{-at} + B\epsilon^{-bt} + C\epsilon^{-ct}$$

and conversely the voltage wave will be considered oscillatory when its mathematical expression takes the form

$$e = M\epsilon^{-mt} + N\epsilon^{-nt}(\cos \omega t + Q \sin \omega t),$$

where all the symbols are constants except e and t. While the smooth-wave form of the equation could express a wave that would cross the zero-voltage axis, this does not usually occur in a circuit of 5 constants (figure 2 in paper) for ordinary values of the circuit constants." This definition of a smooth wave was used in the paper. For practical purposes the wave could be considered smooth even though the part

$$N\epsilon^{-nt}(\cos \omega t + Q \sin \omega t)$$

in the oscillatory form amounts to one per cent or more of the voltage at its crest. This idea also was used in the paper to allow for the rigorous use of the relation

$$L_1 = R_1^2C/4$$

because even when using this relation the oscillatory form of impulse-voltage test wave does generally result as indicated in the paper. This also falls in line with Mr. Sprague's thought of increasing the inductance to the value of L_1 demanded by this relation. In general this is a good idea but normally increasing L_1 increases the wave front, and depending upon the wave shape desired, it might be better to juggle the values of R_1 and R_2—this gives a minimum wave front with a maximum economical crest for a practically smooth wave.

There is one idea in this paper that I believe should be emphasized again and that is this: Considering the mathematical expression of the voltage wave applied to the test piece, as long as the ratios K_1 and K_2 are constant and

$$L_1 = R_1^2C/4$$

all test waves will be identical throughout.

Mr. Hagenguth has presented some very useful approximate equations and has shown their accuracy with examples. Such equations should be very helpful in reducing the time required to select circuit constants. Mr. Hagenguth has also referred to the usefulness of the electrical transient analyzer[1] which is a valuable adjunct to any laboratory doing impulse work.

Mr. Bellaschi has brought out a point which may have been overlooked in the paper by some readers—that is, that figure 2 in the paper is for only a capacitance load. In his discussion Mr. Bellaschi apparently overlooked the fact that the original investigators, Steinmetz and Peek, had analyzed the behavior of the impulse generator considerably earlier than 5 years ago.

Dr. Harding has indicated the need of co-ordinating the data obtained in various impulse-voltage laboratories and to this I will add that there is the ever present need of reducing the time and cost of making tests.

References

1. The Oscillograph Electric Transient Analyzer, N. Rohats. *General Electric Review*, volume 39, March 1936, pages 146–9.

Short-Time Spark-Over of Gaps

Discussion and author's closure of a paper by J. H. Hagenguth published in the January 1937 issue, pages 67–76, and presented for oral discussion at the instruments and measurements session of the winter convention, New York, N. Y., January 28, 1937.

C. S. Sprague (Purdue University, Lafayette, Ind.): The shielded resistance divider described by the author seems to be the first real attempt to make this type of divider suitable for fast fronts and very short times. With regard to this divider the writer wishes to ask what length of resistance wire is used to obtain the 7,000 ohms employed in the divider. The voltage applied to the entering end of the cable arises, in part, from the current flowing through the resistor, and in part from the induced charges due to the shielding and ground capacitances. With very steep waves the latter must form a reasonable percentage of the total, especially on the rising wave front; if not, then there would be no need for shielding. That portion of the voltage at the entering end of the cable, arising from the capacitance effects, is presumably applied simultaneously with the rising voltage at the top end of the divider, while that portion resulting from the surge current flowing

through the resistance is not applied until the wave has traveled over the length of resistance wire between the top end of the divider and the cable connection. There is also the fact that the induced charges are continually leaking to ground during the short interval before the current wave has traversed the entire length of the resistance wire. The argument becomes complicated and will be carried no farther, however, it seems remarkable that the resistance dividers when used for such fast fronts are as satisfactory as they are stated to be.

With reference to the author's figures 4*a* and *b* the writer agrees with the author as to the elimination of L_g in so far as possible. However, where some L_g must be tolerated, it appears that the impulse generator and oscillograph grounds could be made to the circuit at the lower end of R_d, providing the voltage drop across L_g was not too high so as to damage charging equipment, etc.

For some time the writer has contended that short-time flashover and breakdown values are considerably affected by the amount of series resistance and inductance in the generator circuit. It is gratifying to have this confirmed in the author's figure 5 and thus lend further support to the suggestion that surge generator constants, or at least their range, should be specified as well as the wave shape.

K. B. McEachron (General Electric Company, Pittsfield, Mass.): There appears to be a real need for a high-voltage divider, to be used in laboratories where impulse testing is carried on, which will successfully reproduce steep-fronted waves and still be compact in design and uninfluenced by surrounding fields. Such a divider Mr. Hagenguth has described, and should prove to be very useful indeed. Additional tests are of course necessary in connection with this divider, so that all of its uses are completely understood, but the data presented by Mr. Hagenguth appeared to indicate quite clearly that it gives results which may be relied upon. It is, of course, unfortunate that no standards exist in this field of measurement when times shorter than a microsecond or so to breakdown are considered.

I hope that this paper will not be interpreted in any sense as being intended to propose steeper and still steeper waves for impulse testing of apparatus. From my experience relating to surges due to natural lightning, either at the point of inception or elsewhere, there seems as yet to be no indication that waves having an over-all steepness much in excess of 1,000 kv per microsecond need be considered.

It is true that much of our information along this line is deductive and based to a considerable degree upon the effects observed of direct strokes on apparatus and structures of one sort or another. These observations are, of course, coupled with results of tests made in the laboratory where wave shapes are known, and there does not seem at this time much justification for further increase in the rate of rise of test impulse waves.

From the point of view, however, of being certain of the accuracy of the results for the steepness of waves expected in practice, it is quite desirable that our measuring equipment be so designed and operated that measurements can be taken at rates of rise considerably in excess of those expected. These additional data points will lend support to the accuracy of those points within the expected lightning range, and help to appreciably increase our confidence in the results obtained. It would seem, therefore, in the absence of data to indicate these ultrasteep waves, that we would do well to confine our co-ordination studies to waves not exceeding 1,000 kv per microsecond at least, until such time as field data indicate that still steeper waves are to be encountered in practice.

There is one situation in which waves may appear whose steepness compares with that found in the laboratory, and this is the case of flashover between one conductor and another where the time to breakdown would be of the same order as observed in the laboratory for the same distances.

In Mr. Hagenguth's paper, mention is made of the difficulties involved in describing the front of the wave in those cases where sufficient prespark-over current is drawn to cause the applied voltage wave to depart from its normal expected rise. It seems to me that the best answer to this situation, from the point of view of the testing laboratory, is to so proportion impulse-generator capacitances, and load capacitances and series resistance that this turning over characteristic will be so small as to be negligible. If this result can be obtained, then the kilovolts at breakdown divided by the time to breakdown would give a correct rate of voltage rise, assuming of course that the zero of time was determined by the intersection of the line drawn through the 10 and 90 per cent point on the front of the wave and its intersection with the time axis. To get such a rate of rise with a sharp breakdown when testing on the front of the wave may require some modification in some of the impulse generators now in use, but it certainly would prevent considerable confusion with respect to the meaning of the data obtained.

H. L. Rorden and **P. M. Ross** (Ohio Brass Company, Barberton, Ohio): In surge-voltage testing, the accuracy of recorded waves and voltage calibration has been the object of much discussion and question. The voltage divider is a necessary part of surge testing and its accuracy might well be questioned, since with high voltages an accurate means of calibration or check is lacking. When the new laboratory of the Ohio Brass Company was put into operation in 1934, one of the major items of consideration in the design of the surge generator was to obtain an electrostatic field which, inherent to the design, would be substantially uniform throughout the height of the generator, illustrated in figure 1. The divider is placed in the field adjacent to the generator structure, which is built in the form of a helix. In each revolution of the helix a capacitor is close to the divider and maintains a voltage proportional to its physical height above ground. This results in a uniform voltage distribution throughout the length of the divider and is a desired condition for accurate reproduction at the oscillograph.

At the several available junctions of the divider the potential differs by less than 3 per cent from a uniform distribution. For further check, volt-time characteristics of spheres were obtained, the results of which are in close agreement in the $^1/_4$-microsecond region with Mr. Hagenguth's figure 15.

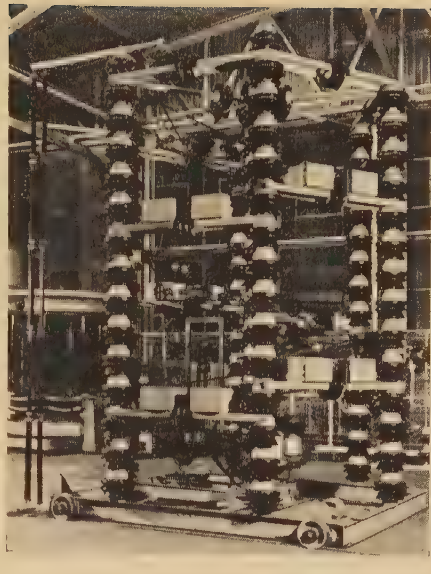


Figure 1. The Ohio Brass Company surge generator

In many of its features this generator fits the description suggested by Mr. McEachron in his discussion as being desirable. Due to the helical design it is compact; it has a substantially uniform voltage distribution; the entire generator including the divider is portable. The divider and other circuit resistors are enclosed in porcelain, also the supporting insulation is porcelain. The generator may be used outdoors without damage in the event of inclement weather.

In his figure 5 showing the change of wave shape with a change in circuit constants, we believe Mr. Hagenguth has touched upon an item which should receive serious consideration in setting up standards of surge testing. Other investigators directly familiar with surge testing have undoubtedly observed this phenomenon. It seems very evident that considerable energy is required to charge corona and ionization streamers prior to complete breakdown. Insertion of damping resistors in surge generators is very necessary, since otherwise it seems impossible to obtain uniform waves. The damping resistance so limits the available energy at the test that prior to breakdown the voltage across a gap falls appreciably from that of its normal wave shape. This becomes increasingly greater with overvoltages and appears to be present in all cases where flashover is dependent upon the completion of corona streamers.

An outstanding example of the inability of surge generators to maintain their wave shape before spark-over is illustrated in figure 2. This illustration, with additions, is reproduced from the March 1936 *Journal* of the British IEE. The limitations mentioned are very evident. It may be observed that the final flashover of the overvoltages occurs below the wave of the minimum flashover. These authors have proposed to set up British standards of testing on the basis of their results, which would seem to be of questionable accuracy.

We have also noticed this phenomenon to be present, although to somewhat lesser degree, if the damping resistance is removed. Also it is greater with generators of low energy, such as were used by early investigators when the so-called 1x5 wave was proposed as a standard for testing. It is now generally recognized that with the generators of higher energy in use, the 1x5 wave so limits the available energy and voltage for test, due to the necessary high damping resistance, that it is undesirable for test purposes. This wave was readily obtained in generators of low energy but imposes a serious handicap on present methods.

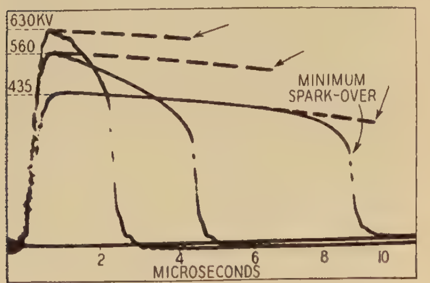


Figure 2. Spark-over at voltages in excess of minimum impulse spark-over

Surge testing is complicated by several such limitations and we wish to stress the importance of this point which Mr. Hagenguth has touched upon.

P. L. Bellaschi (Westinghouse Electric & Manufacturing Company, Sharon, Pa.): The paper by J. H. Hagenguth is a further contribution on the short-time spark-over of gaps and to the technique in obtaining such data. In attempting to compare his results to data published in the past few years, the first question which arises is one on method of scaling oscillograms and plotting data.

It has been and is the common practice in testing with impulse voltages chopped on the front to specify the steepness of the front in kilovolts per microsecond and the crest voltage. In table I the results from typical oscillograms are given. In the first column the steepness of the front is determined according to established definition, that is drawing the line of the slope through the 2 points on the oscillograms at 10 per cent and 90 per cent the crest value. Circuit conditions present in practical testing often result in some superimposed oscillations on and distortion of the main component of the rising front. Some judgment is necessary in applying the 10 per cent–90 per cent definition and this is best done scaling the steepness of the front along the major component. The second column of table I gives the values determined from the application of this practical method. It shows that the results in general are in substantial agreement with those applying the 10 per cent–90 per cent rule. In the third column the time-to-breakdown has been employed to calculate the rate of voltage rise (average). It is apparent that the results from this third method are not in general comparable to those from the first 2 methods.

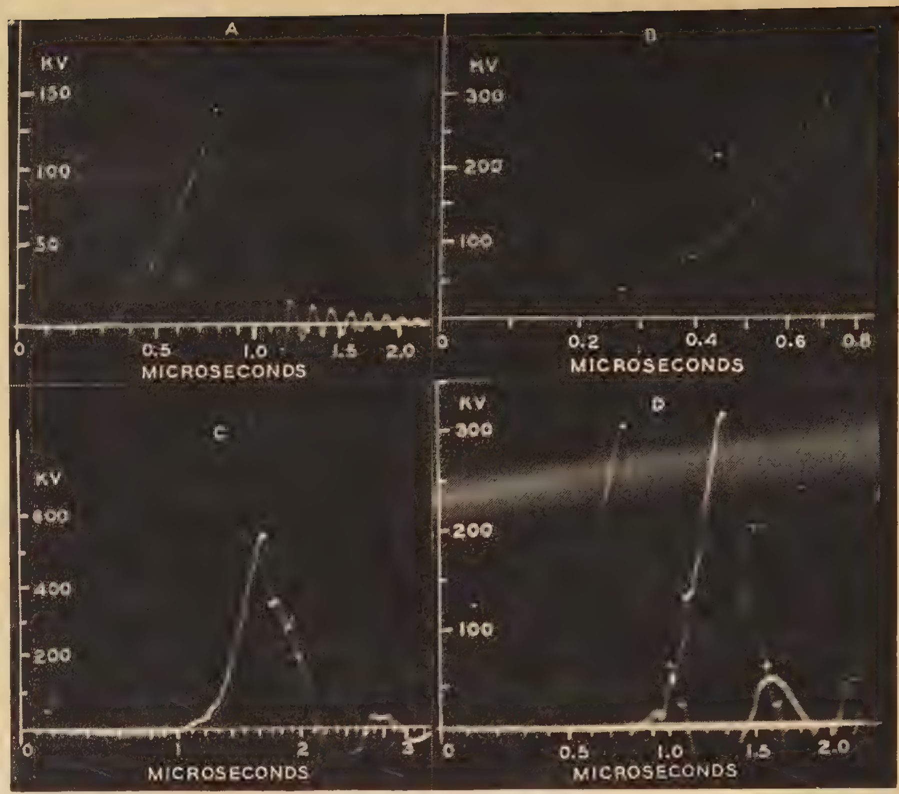


Figure 4

The values in column 3 are 10 to 20 per cent lower than those in column 2. Considering the different methods, it will be seen that the data for the rod gaps in figure 9 (by the author) are in better agreement with the previously published data (Electrical Engineering, June 1934, page 870 and Electrical Engineering, September 1936, page 985) than it may appear from a superficial comparison. The data in the paper and those reported by the writer for bushings, insulators, and similar equipment (*Electric Journal*, June 1936, page 274) are substantially in the same order considering the character of the tests. It would have been well had the author called attention that his data for solid and for the combined solid and liquid insulation applies for single or a limited application of tests.

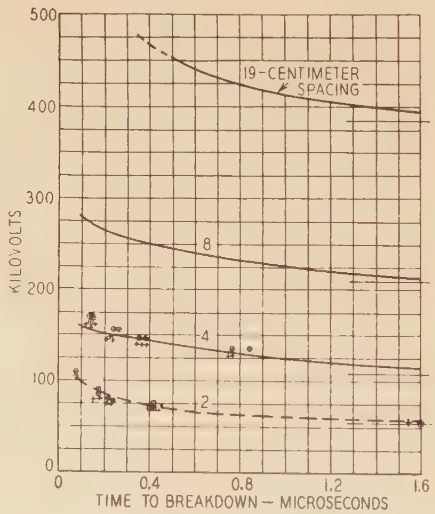


Figure 3. Spark-over voltage of 25-centimeter sphere gap on positive impulse

Crosses represent resistance-divider measurements (recent data)

Circled crosses represent capacitance-divider measurements (recent data)

Curves in solid lines are from figure 6 of "Sphere Gap Characteristics on Very Short Impulses," *Electric Journal*, volume 32, March 1935, page 120

Table II gives data for rod gaps which were taken recently in the course of ordinary tests. These data have been scaled according to the established technique (method in column 2 of table I) from such oscillograms as *C* and *D* of figure 4. A comparison of these sample data with those first presented to the AIEE (Electrical Engineering, June 1934, page 874, figure 6) shows adequate agreement from a practical standpoint. This shows that the methods and technique used can give practically good results. In this connection it is well to note that departures from the average of some ±10 per cent for the voltage and about ±20 per cent for the rate of rise are to be expected and such variations should be considered permissible at the present. That these and even greater variations are present and inherent in work of this kind will be evident also from a close study of the data in figure 8 of the paper. The smoothness of this curve at the short times is more apparent than real.

There are a number of points which come to the attention in studying this paper:

(*a*). According to the author, the method of measuring steepness in terms of time to breakdown comes into the picture because of the flattening effect on the crest of the wave when a high series resistance (2,000 ohms) is used in the generator. Judging from the experience in a good many laboratories the series resistance more commonly used is about 400 to 500 ohms. Besides, as the author suggests, this resistance could

be removed partially or altogether to get the steep fronts when the load is of high capacitance. Because of this the flattening effect would not be expected in any great amount in the more common test arrangements.

(*b*). While the steeper fronts are obtained by the removal of the series resistance there are disadvantages entailed from this practice. For example, it is often convenient or desirable to have an identical setup of the generator to test the same gap or apparatus with either the $1^{1}/_{2}$x40 microsecond wave or a steep-fronted impulse. Another disadvantage would be that the effects of leads are accentuated upon complete removal of the series resistance.

(*c*). The scheme in figure 4 (*b*) of the author in attempting to reduce the effect of voltage drops in the ground discharge circuit has been recognized. There are physical limitations to the degree this method can actually be applied. There are other possibilities and approaches possible to minimize the ground effects such as the following. Good results are obtained keeping the cable of the divider away from the discharge circuit or insulating it from ground. It should also be possible to ground at the test piece and connect this grounded end directly to the generator by means of cables so as to confine the discharge currents in a definite known path.

The data on the short-time spark-over of the 25-centimeter sphere gap in figure 15 of the paper are substantially in disagreement with the results obtained by the writer and W. L. Teague from tests on this size of sphere gap at exactly the same spacings (*Electric Journal*, March 1935, page 120). For example the data for 4-centimeter spacing at a time to breakdown of 0.2 microsecond is 40 per cent higher in figure 15 than in the corresponding data plotted essentially on the same basis which appears in figure 6 on page 122 of *Electric Journal*, March 1935.

Table I. Comparison of Methods of Scaling Oscillograms to Determine the Rate of Rise of Voltage

Method by 10 Per Cent to 90 Per Cent Definition Kv/Microseconds	Method Averaging Front on Main Component Kv/Microseconds	Method Using Time-to-Breakdown Kv/Microseconds	Oscillogram Crest Voltage Kv
1,460	1,360	965	820
2,600	2,320	2,300	1,310
1,880	1,875	1,620	1,315
2,750	2,440	2,400	1,100
3,000	3,140	2,370	1,160
1,850	1,990	1,440	1,035
2,070	2,150	1,520	1,035
1,330	1,450	1,160	640
1,140	1,220	1,040	855
640	695	520	835
620	640	570	895

Table II. Sample Data on Rod-Gap Breakdown on Front of Wave

Gap Spacing (Inches)	Polarity of Impulse	Crest Voltage* (Kv)	Rate of Rise Kv/-Microseconds
5.75	Positive	261	500
5.75	Positive	300	620
5.75	Positive	313	800
5.75	Positive	320	840
10.0	Negative	500	1,245
10.0	Negative	520	1,475
10.0	Negative	515	1,460
20	Negative	770	1,110

* Rad = 1.0; Humidity = 2.0 to 3.4 grains per cubic foot.

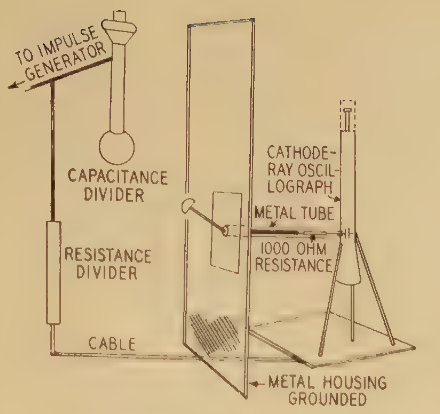


Figure 5

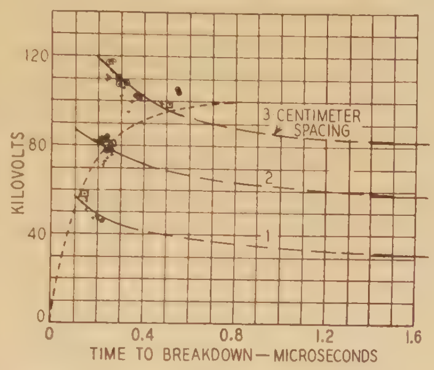


Figure 6. Spark-over voltage of 12.5-centimeter sphere gap on positive impulse

Crosses represent resistance-divider measurements
Circled crosses represent capacitance-divider measurements
The squares give the data for the one-centimeter, 2-centimeter, and 3-centimeter spacings reported by A. K. Nuttal (*Journal* of the Institution of Electrical Engineers, February 1936, page 229), and the dotted curve indicates the fully developed wave used in these tests

Since taking the data in the *Electric Journal*, check tests have been made from time to time with substantially good agreement. Recently a series of check tests have been made in a different laboratory from the one where the original data were taken. Results of these tests for the 2- and 4-centimeter spacings are plotted in figure 3. Approximately half the measurements were recorded at the cathode-ray oscillograph with the resistance divider having a resistance of 3,300 ohms and with a short cable (surge impedance equals 44 ohms). The other half of the tests were recorded with a capacitance divider. Figure 5 shows the test and measuring setup. Oscillograms recorded are given in figure 4 (*A* and *B*). A study of these data leads to the conclusion that the 2 dividers are in good agreement. It further shows that the use of these 2 methods of measurement has the great advantages of confirming results and establishing confidence in measurement.

At the same time these check tests were made on the 25-centimeter sphere gaps data were taken also on the 12.5-centimeter sphere gap for spacings of one centimeter, 2 centimeters and 3 centimeters (plotted on figure 6). On this same figure are also plotted data obtained by A. K. Nutall (*Journal* Institution of Electrical Engineers, February 1936, page 229) on the 12.5-centimeter sphere gap for these same spacings by means of a cathode-ray oscillograph of such construction that the measurements are directly recorded at the oscillograph plates. The agreement between data obtained from the 3 methods of measurement (figure 6) is amply close for all practical purposes. Because of this good agreement there are good reasons to question the data of figure 15 in Hagenguth's paper.

In conclusion it is gratifying to note the progress that has been made possible through the application of the resistance divider. The resistance divider has come into wider use in the past few years and in greater favor. A good number of laboratories in the country are now also using the capacitance divider. Experience has shown that the judicious use of these 2 methods of measurement can fulfill most if not all practical requirements, in impulse voltage measurements.

J. H. Hagenguth: The discussions are principally related to the divider, effect of circuit constants, and the steepness of waves and will be taken up in that order.

In answer to Mr. Sprague the length of wire used in the divider described is approximately 850 feet. However, the total physical length of the resistance elements is only 6 feet. A brief attempt was made several years ago to determine the velocity of wave propagation on an ordinary resistance divider, using 2 dividers of approximately equal resistance (see figure 7*a*) but of different physical length both as regards actual length of wire and length of divider. The ends of these 2 types of dividers were connected through cables of equal lengths to the 2 pairs of plates of the cathode-ray oscillograph.

If, as expected the current must be established in a divider of this type by traveling along the wire only, the pattern obtained should have been of the form shown on figure 7*b*, i.e., the voltage at the plates connected to the short divider should have increased first and approximately one microsecond later, assuming a velocity equal to the speed of light, the voltage at the other pair of plates should have increased. However, the actual oscillogram obtained was of the form as shown on figure 7*c*. The wave used for this test is shown on figure 7*d* and had a front of approximately 0.2 microseconds.

This test seems to indicate that the voltage transmission on a divider of this type is a wave phenomenon of somewhat the nature of a space wave traveling along the divider. An exact physical interpretation of this phenomenon has not been attempted on account of the more urgent problem of finding a divider which could be used with confidence to measure impulse voltage with steep fronts. It is, however, an intriguing problem and well worth while of study.

Standards for determining the accuracy of dividers for measuring steep wave fronts are not available, as pointed out by Mr. McEachron. Three methods have been used to obtain proofs for the correctness of the

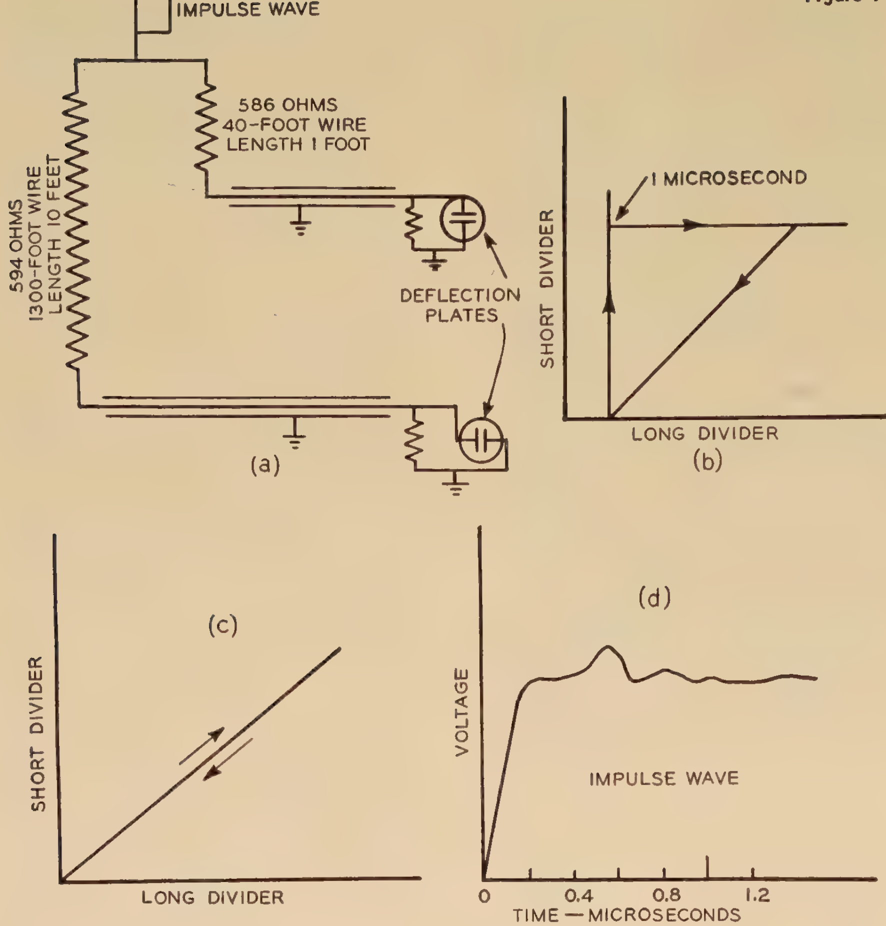


Figure 7

solution: First, the use of the spark-over of a sphere gap strongly irradicated (figure 1 of paper) represents a relative proof, since the actual wave front is not known. The fact, that a spark-over of the sphere occurs after the crest, which is reached in 0.1 microsecond, shows that the divider will be suitable for measuring fronts of 0.4 microsecond or longer, which represent the output of large high-voltage generators. Second, a comparison between a calculated wave and waves measured with 3 different resistance dividers as shown on figure 8. The calculated waves measured with shielded and the low resistance divider check fairly well. The third method consists in checking the input and output voltages of the shielded divider by means of the electrical transient analyzer, and comparing the result with other types of dividers such as a small capacitance divider. The waves applied during such tests have fronts of approximately 0.05 microsecond.

Messrs. Rorden and Ross show a divider shielded by the impulse generator and claim that the voltage distribution along the divider is practically uniform. It is gratifying to know that the author's results on sphere gaps are checked with this arrangement. Without knowing how this distribution was measured and with what type of wave, it is not possible to interpret this result correctly.

There are several objections: (1) The divider has to be used in this one position requiring relatively long leads between divider and testpiece; (2) the shielding cannot be checked conveniently and the divider may be under- or overcompensated.

For elimination of inductance L_g in the ground leads compromises have to be made, since for spark-over tests on the range of 0.5 microsecond or less voltages of the order of 1,000 kv will occur across a wire of 30-foot length.

All are agreed that it is well to arrange discharge circuit to obtain an essentially straight voltage rise, thus eliminating one of the variables of the problem of front of wave testing. Mr. Bellaschi shows in his table I the values of rate of rise of several oscillograms obtained by 3 methods. Differences between method 1 and 2 are of the order of 10 per cent while differences between 1, 2, and method 3 as proposed in the paper are as much as 30 per cent. The reason for the large differences is the bending over of the wave near the crest. In the cases where 1, 2, and 3 agree the front is probably straight, in the other cases bending over occurs. This bending over is, however, not as confusing as it appears as is shown on figure 9 of this discussion. Curves A_1 and B_1 were plotted using conventional methods of definition of kv/μs rise, for A_2 and B_2. The method proposed in the paper was used. Spark-over without series resistance (A_1 and A_2) took place partly on the tail of the wave at about one microsecond, while at short times to spark-over (0.25 microsecond) the voltage rise was straight with a sharp breakdown point. The waves

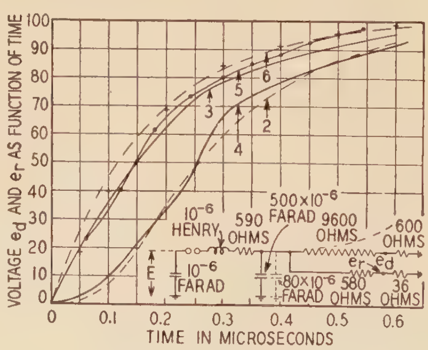


Figure 8. Calculated and tested wave shapes with resistance divider

1— $1/2 x \infty$ wave (calculated)
2—Resulting voltage e_d of high-resistance divider (calculated)
6—Positive wave calculated for circuit constants shown below
3—Measured with 580-ohm resistance divider (EL-1079-106)
4—Measured with standard 10,000-ohm divider (EL-1079-107)
5—Measured with shielded 10,000-ohm divider (EL-1079-108)

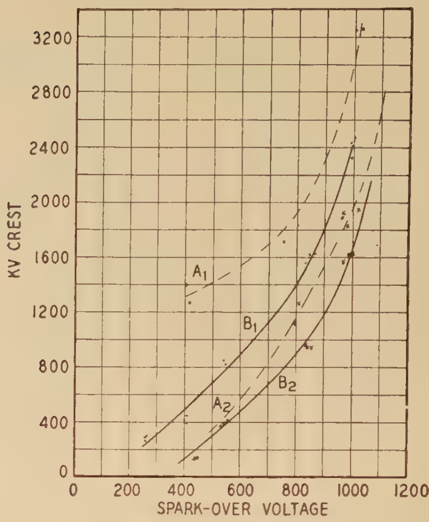


Figure 9. Spark-over voltage of a 22.5-inch rod gap

A_1, A_2—Series resistance is zero
B_1, B_2—Series resistance 1,500 and 2,000 ohms
Curves 1—Kilovolts/microseconds determined as kv crest divided by the time given by the intersection of a line drawn through the 10-per cent and 90-per cent points with the zero axis and the kv-crest axis
Curve 2—Kilovolts/microseconds determined is kv crest divided by time to spark-over

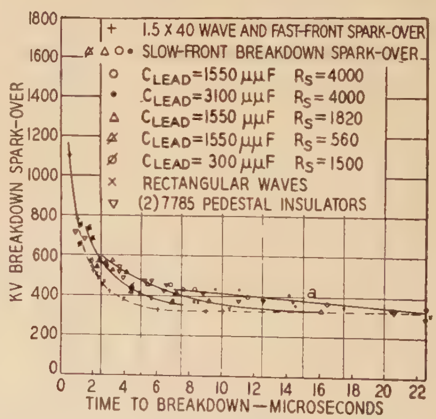
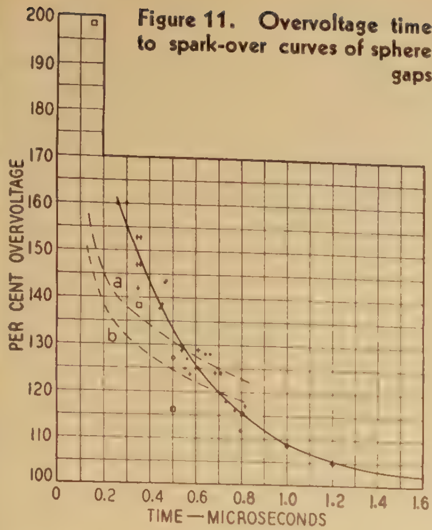


Figure 10. Front-of-wave tests on 20-inch rod gaps

Positive polarity; standard conditions

Figure 11. Overvoltage time to spark-over curves of sphere gaps



Solid curves—Average for 25-centimeter and 100-centimeter spheres; tests with shielded divider
+—Positive polarity, 50-centimeter sphere, 16.7-centimeter spacing
•—Negative polarity, 50-centimeter sphere, 16.7-centimeter spacing
o—Average of 100-centimeter sphere, 23- to 40-centimeter spacing
Nuttal (*Journal* of the Institution of Electrical Engineers, February 1936), direct measurements without divider
Dotted curves—Bellaschi, 25-centimeter sphere, 4-centimeter spacing
(*a*)—Capacitance divider
(*b*)—Resistance divider

of curves B_1 and B_2 showed the bending-over effect shortly before spark-over occurred. In spite of the different nature of the waves used to arrive at these curves, curves A_2 and B_2 practically fall together, and are checked with waves having straight voltage rise at all rates of rise. It appears therefore that the method of average rate of rise would produce more consistent results.

Neither definition, however, seems to fit conditions for spark-over on the front of the wave, when spark-over takes place at a time in excess of one microsecond. Figure 10 shows spark-over of a 20-inch rod gap when waves with slow exponential fronts are applied. Two limits appear to exist: (*a*) spark-over due to a rectangular wave (or practically speaking a 1.5x40 wave) and (*b*) the spark-over due to straight line rise of voltage (or practically curve *a* with a time constant, $RC = 12$ microseconds). That waves with such slow rates of voltage rise cause arc-over on transmission system has been shown by Berger (Lightning Investigation During 1932 and 1933 in Switzerland, K. Berger. ASE Bulletin No. 9, April 27, 1934). For slow wave front tests it appears desirable to indicate rate of rise by the time constant of the wave front to permit comparison between results obtained by different investigators.

Concerning comparison of results published by Mr. Bellaschi and his associates and in the paper, it appears that the differences of rod-gap spark-over obtained are of the order of 10 to 20 per cent for larger spacings, i.e., spark-over values obtained with the shielded divider are higher by about that amount, when compared on the same basis (average rate of voltage rise). The values obtained with the shielded divider usually check within 10 per cent under entirely different test conditions, with different generators, oscillograms, and operating personnel. That the differences in results between the 2 laboratories is not greater than 10 to 20 per cent is undoubtedly due to the fact, that Mr. Bellaschi uses a 1.5x40 wave. For a front of such relatively slow rise the distortion effect of the nonshielded resistance divider is relatively small. However, as pointed out in the paper, the 1.5-microsecond front cannot economically be used for front-of-wave tests on gaps in excess of 30 inches and it should, therefore, be expected that results for the larger gaps should show greater differences.

It is not quite clear why it should be desirable to use an identical generator setup for both the 1.5x40 wave and the steep-fronted impulse. A standardized front is desirable for full-wave test and expecially the elimination of oscillations superimposed on the crest of the wave is of great importance; for front-of-wave tests, however, limitations on the actual front used should not be imposed except to specify the rate of voltage rise, or the time to spark-over. The removal of the series resistance does not materially increase testing difficulties provided the divider is connected directly to the testpiece.

Much greater differences in results, are found when comparing the spark-over of sphere gaps, as pointed out by Mr. Bellaschi. From figure 3 and figure 6 obtained by Mr. Bellaschi using a resistance type and capacitance divider it appears that spark-over voltages obtained with the capacitance divider are consistently higher than those obtained with the resistance divider which seems to indicate that even a resistance divider of as low a value as 3,300 ohms will not reproduce correctly the true rate of rise. In figure 5 of this paper is replotted an average curve obtained recently on a 50-centimeter sphere gap with 16.7-centimeters or 33.4-per cent spacing with points indicating negative polarity and crosses positive polarity. The large circles on this curve represent average values obtained from tests on a 100-centimeter sphere gap with spacing varying between 23 and 40 centimeters. Other recent data obtained with a 25-centimeter sphere gap fall within 10 per cent of the plotted curve. The squares indicate the points published in Mr. Nuttal's paper similar to those in figure 6 of Mr. Bellaschi's discussion. Finally the 2 dotted curves represent values of figure 3 of Mr. Bellaschi's discussion for 4-centimeter spacing. A comparison of the overvoltage values of the 50-centimeter and 100-centimeter sphere seems to indicate that the characteristic spark-over curves of the 2 sizes of gaps agree very well, also Nuttal's results obtained on a much smaller gap of 12.5-centimeter diameter indicate the same general trend. The curves of figure 1 of Mr. Bellaschi's paper, especially the values obtained with the capacitance divider agree fairly well in the region for spark-over times of 0.4 microseconds and longer. In the region of short-time spark-over the curves do not check, which possibly is due to the distorting effect of the resistance divider and possibly due to the effect of the resistance divider on the field in the capacitance divider, which apparently were placed quite close as shown in figure 5 of Mr. Bellaschi's discussion.

In conclusion the author wishes to emphasize the point brought out by Mr. McEachron that the paper should not be interpreted as advocating the use of increasingly steeper fronts for impulse testing. It is merely intended to discuss the problem of voltage measurement and to show the effect of steep wave fronts on the spark-over of the component parts of transmission systems.

A much greater amount of field data would be required to justify testing with fronts having rates of rise in excess of 1,000 kv per microsecond.

Currents and Potentials Along Leaky Ground-Return Conductors

Discussion of a paper by E. D. Sunde published in the December 1936 issue, pages 1338–46, and presented for oral discussion at the communication session of the winter convention, New York, N. Y., January 25, 1937.

K. L. Maurer (Bell Telephone Laboratories, Incorporated, New York, N. Y.): The earth as a conductor of electricity has long been a puzzling and troublesome subject because of its great extent, its amorphous structural arrangement, and its general lack of homogeneity. The tendency upon the part of the engineer dealing with practical problems involving the earth as a conductor, has been to get around the uncertainties either by ignoring them or by idealizations often more consistent with convenience than with the facts. Fortunately, in many types of circuit problems, propagation rates are slow enough to admit rather sweeping idealizations of the electrical behavior of the earth. In other types of circuit problems, some of which are mentioned in the paper, and in particular, those involving differences in potential between points on the ground itself, recognition of what actually takes place in the earth cannot be avoided. In the past 10 years or so, a great deal of work

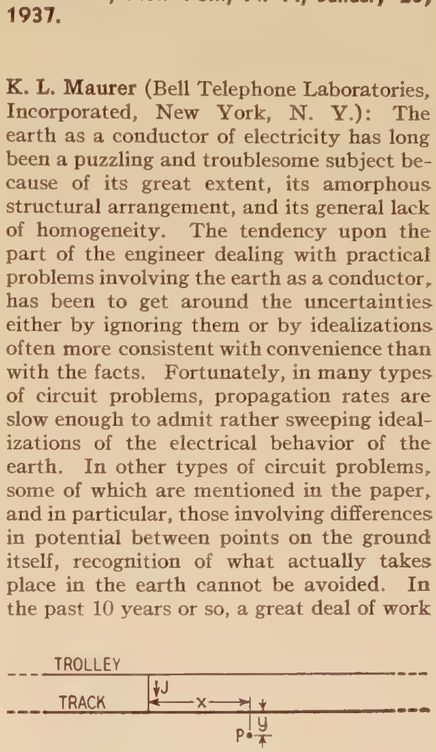


Figure 1

on this subject has been done by a number of investigators, as a result of which many of the difficulties have been resolved, and to this work Mr. Sunde's paper is an important contribution.

The formidable appearance of the expressions for voltage and current may, at first glance, give the impression that the formulas are too unwieldy for practical use. As a matter of fact, in most practical applications it will be found that the expressions can be considerably simplified without overstepping the limits of engineering accuracy, because it is rarely if ever that all of the factors in a circuit problem involving the earth can be determined with enough assurance to justify carrying out all of the steps called for in the formulas. The main factor of uncertainty, of course, is the character of the earth in the locality in question. As may be seen from the formulas in table II, the earth resistivity, although of secondary impor-

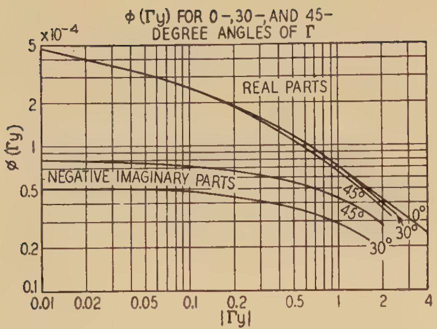


Figure 2

tance in the expressions for the conductor current and voltage, is an extremely important factor in determining ground potential since the latter is almost directly proportional to the resistivity. Since it is known by experience that the earth, particularly at the surface, usually is far from homogeneous, and since it is practically impossible to determine the variations in resistivity over the entire area involved in a particular problem, the question of the reliability of the formulas in practical work naturally arises.

To answer this question, a rather extensive series of tests was undertaken in the summer of 1935. The leaky ground-return conductor for these tests consisted of a single electrified railway track, and particular attention was given to the investigation of ground potentials, such as might affect communication circuits in the vicinity. From the results of these tests, which are described in another discussion of this paper, and from several other experimental checks, it appears that in the average case, a reasonably good fit between the formulas and the experimental data can be expected with relatively simple hypotheses as to the earth's structure.

As an example of the extent to which the formulas in the paper can be simplified for engineering use, consider the expression on page 1343 for ground potential produced by an electrified railway, as at point P in figure 1 of this discussion. Since ground potentials are largest close to the track, it is of practical interest to examine this formula for small values of separation. By means of the expressions in table II, the ground potential for small values of y may be written (using the notation of the paper):

$$V_e(x, y) = \frac{J\rho\Gamma}{4\pi}(1 - \mu) \times \left[K(x) + 2e^{-\Gamma x}\log_e\frac{1.12}{\Gamma y}\right] \text{volts} \qquad (1)$$

in which $K(x)$ is a quantity, independent of the separation which is found to vary only slightly over the practical range of values of Γx. In obtaining the difference in ground potential between 2 points at a given value of x, the quantity $K(x)$ cancels out and in obtaining the difference in ground potential between 2 points at different values of x, the difference between the 2 values of $K(x)$ is small compared to the difference between the 2 values of the remaining term, since the latter varies exponentially with x. Therefore, for close separations (up to about 500 feet in the average case), it is permissible to ignore $K(x)$.

Since the largest values of ground potential at a given separation occur opposite the current source or the load, it is also of practical interest to examine the formula in the paper for small values of x. In this vicinity, the ground potential may be written as

$$V_e(x, y) = J\rho\Gamma(1 - \mu)e^{-\Gamma x}\phi(\Gamma y) \text{ volts} \qquad (2)$$

For convenience in practical work the terms of equation 2 are defined as follows:

J = trolley current, amperes

ρ = earth resistivity, meter-ohms

$\mu = M/Z$ = ratio of mutual impedance of trolley and return system to return system self-impedance, both on an earth return basis

x = distance along track from point opposite electrode at which ground potential is taken, to point at which current enters tracks, miles

y = separation, normal to track, between electrode and track, miles

$\Gamma = \sqrt{G \cdot Z}$ = track-return-system propagation constant, per mile

$G = (g \cdot g_1)/(g + g_1)$ = track-return-system leakage conductance mhos per mile

g = leakage conductance of ties, track ballast, and other leaks, such as catenary structure footings, etc. For tracks, this quantity has been found to vary between 0.5 and 2 mhos per mile per track for dry and wet weather conditions, respectively. One mho per mile per track is frequently used as a representative value

g_1 = "leakage conductance" relating to the earth in the vicinity of track. This quantity may be taken as $1{,}000/\rho$ mhos per mile, regardless of the number of tracks

$\phi(\Gamma y)$ = a function of the return-system propagation constant and electrode separation, containing factors for conversion of distances from meters to miles. This function is shown in the accompanying figure

At $x = 0$ equation 2 is valid for a large range of values of Γy. As x increases, however, the range of values of Γy for which the equation is accurate becomes narrower. For Γx larger than about 2 in the average case, the equation is restricted to separations about the same as those for equation 1. At large values of Γx, however, the ground potential ordinarily is so small compared to that at small values of Γx, that its accurate determination is of less practical importance.

The ground potential produced by current leaving the track, as at a substation, is calculated in the same way, but has reversed sign. The total ground potential produced by current entering the track at one point and leaving at another, as in a section between a load and a substation, is the algebraic sum of the potentials calculated for each point separately. The difference in ground potential between 2 electrodes is the difference between the ground potentials calculated in this way for each point independently.

P. Goldstone (Gibbs & Hill, Inc., New York, N. Y.): In the preceding discussion reference was made to certain tests to obtain experimental checks on the analysis given in the paper. In these tests, in which I was interested from the railroad viewpoint, in addition to the study of ground potentials, measurements were also made of track currents and potentials, which are of interest to the railroad engineer.

The test arrangements are shown in figure 3. The circuit, which represents the trolley-track circuit of an electrified railway, consisted of a single overhead wire with return in a single bonded track. The tests were made at one end of the circuit and circuit lengths of 1, 2, 3, and 4 miles were used.

Figure 3 shows observations of the following quantities as the length of the energized section was varied: (*a*) track potential measured between the track and a ground rod located at the edge of the ballast, (*b*) difference in ground potential between the ground rod at the edge of the ballast and a ground rod situated about 9,000 feet away on a line at right angles to the track, (*c*) track current flowing away from the energized section. (This current is of course equal to the earth current at the end of the section.) The results indicate that all 3 quantities vary in substantially the same manner as the section length is changed. It will be seen that the track potential changed considerably with weather conditions due to the fact that the moisture increased the track ballast leakage conductance. The effect of weather conditions upon the ground potential, however, was negligible. The ground potentials at points near the track are seen in this case to be of the same order of magnitude as the track potential.

On figure 4 are shown observed differences in ground potential measured between the ground rod at the edge of the ballast and ground rods at various separations from the track along a right angle line. The energized circuit in this case was 4 miles long. Three calculated curves also are shown on this figure. Curves A and B were calculated by methods described in the paper assuming homogeneous earth having values of resistivity of 1,600 and 200 meter-ohms, respectively. Curve C was calculated for a resistivity variable with depth. Comparison of the experimental with the calculated curves brings out the effect of nonhomogeneous earth upon the variation of ground potential with separation. Measurements of earth resistivity by the usual d-c method in the vicinity of the end of the energized section indicated roughly a 2-layer earth structure, in which the resistivity of the upper layer was on the order of 1,600 meter-ohms, while at greater depth the resistivity was on the order of 200 meter-ohms. This condition required extending the formulas given in the paper, which are based on homogeneous earth, to correspond to the case of re-

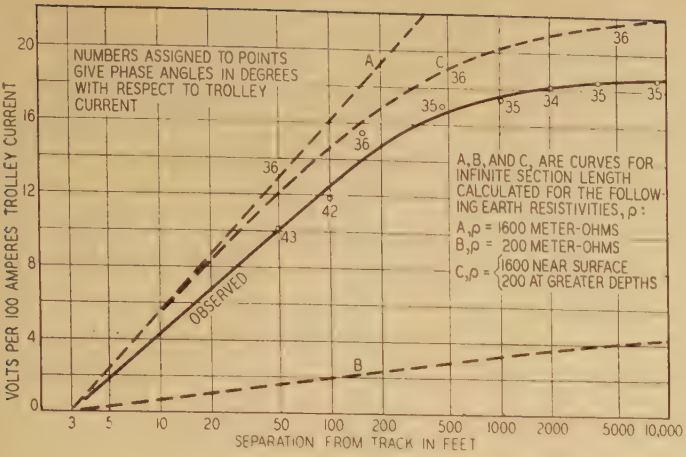


Figure 3. 28-cycle tests on single-track railroad; earth potentials at end of 4-mile section referred to a ground near track

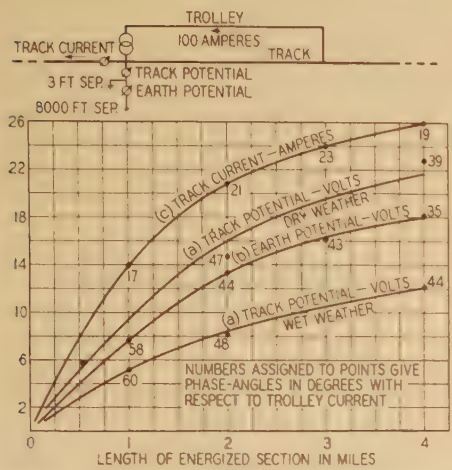


Figure 4. 28-cycle tests on single-track railroad

sistivity variable with depth and curve C on figure 4 is based on this assumption. The calculated curves are based on the assumption of infinite length of the energized circuit whereas the actual circuit was only 4 miles long. This fact accounts for some of the difference between the observed results and the calculated curve C.

Curve C was calculated by the author of the original paper in the following manner. Assume the variation in apparent earth resistivity ρ', with electrode separation r to be given by the formula:

$$\rho' = \rho(1 + ke^{-\beta r})$$

where ρ is the earth resistivity measured for large electrode spacings, $(1 + k)\,\rho$ the earth resistivity for small spacings and β a properly chosen constant. The earth potential is then approximated by calculating the earth potential for homogeneous ground of resistivity ρ for 2 separations y, and

$$y' = y\sqrt{1 + \left(\frac{\beta}{\Gamma}\right)^2};$$

where Γ is the propagation constant of the track for the unit length used for r. The latter earth potential is multiplied by k and added to the first. It was found that the earth resistivities measured in these tests could be approximated by taking $\rho = 200$ per foot, $k = 7$, and $\beta = 0.015$ per foot, and curve C of figure 4 is based on these assumptions

The following conclusions may be drawn from the experiments:

1. Ground potentials, track potentials and earth current at one end of a traction circuit (at which point the potentials normally are largest) vary with the circuit length s nearly as $1 - e^{-\Gamma s}$ and decrease with distance x, along the track from one end of the section toward the center nearly as $e^{-\Gamma x}$
2. If the earth is not homogeneous, but has a resistivity decreasing with depth, the ground potential difference between 2 electrodes, one of which is near the track, increases less rapidly, as the other electrode is moved away from the track, than if the earth is homogeneous
3. With the track energized across a track break (as in case 1 of the paper) the track current propagation is nearly exponential for a considerable distance. This was found to be the case over the entire section (3 miles) used in the tests.

Inductive Co-ordination of Common-Neutral Power-Distribution Systems and Telephone Circuits

Discussion and authors' closure of a paper by J. O'R. Coleman and R. F. Davis published in the January 1937 issue, pages 17–26, and presented for oral discussion at the communication session of the winter convention, New York, N. Y., January 25, 1937.

Sidney Withington (The New York, New Haven and Hartford Railroad Company, New Haven, Conn.): The co-operation which has been accomplished between the power and telephone interests, implied in this paper, I believe should be emphasized.

Reference is made in the paper to the co-ordination between the National Electric Light Association and the Bell Telephone system. Attention is called to the joint effort of the Edison Electric Institute and Association of American Railroads, resulting also in general agreement as to principles and practices, which should avoid a great deal of unprofitable controversy in the future.

Work of this kind which insures that decisions will be based upon engineering principles, is incomparably more desirable than permitting contests in the courts, where decisions by nontechnical individuals may be based upon cleverness of presentation by brilliant lawyers, regardless of engineering merits or economic factors, rather than upon logical analysis founded upon facts.

Instances of this kind have unfortunately occurred in the past, and it speaks well for the engineering profession that means have been taken to keep such discussion out of the courts in the future.

T. A. Taylor (Bell Telephone Laboratories, Incorporated, New York, N. Y.): The paper by Messrs. Coleman and Davis discusses the factors which must be considered in the inductive co-ordination of common neutral power distribution systems and telephone circuits operating in urban areas. As pointed out in the paper, there has been a recent trend toward the use of multi-grounded or common-neutral systems in rural areas and in view of this trend, it may be of interest to compare briefly the co-ordination problems presented in rural areas with those discussed in the paper. This discussion is based upon the results of field studies of this problem carried out during the past 2 years by the joint subcommittee on development and research—EEI and Bell system. A comprehensive report on this work is now being prepared.

As the authors have indicated, rural power circuits are generally longer, operate at lower load densities and frequently at higher voltages than those in urban areas. As a result, it has been found, particularly in the case of rural lines operating at the higher voltages, that the ground-return charging current components are apt to be more important in contributing to their inductive influence than either the load current or transformer exciting current components, which generally control the influence of the lower voltage urban circuits. These "capacitive" or charging-current components return, at least in part, in the ground, regardless of whether the circuit is operated isolated, or with a single-grounded or multi-grounded neutral. The results of tests in a number of locations indicate that while multigrounding the neutral of these longer circuits increases the 60- and 180-cycle ground-return components, it, on the average, makes no substantial change in the components of higher frequency, although in individual cases they may be increased or decreased. Measurements of noise on rural telephone circuits exposed to these power circuits have shown that these higher frequency components tend to control the noise whether the power circuits are unigrounded or multigrounded. On the average, therefore, on circuits exposed to rural power lines operating at 7,600 volts and above, the noise is not materially different whether the power circuit neutral is uni- or multi-grounded.

In the case of short low-voltage rural power lines, the charging currents are of relatively small importance compared to the transformer exciting currents and load components. The behavior of such circuits, when multigrounded, is therefore similar to that of the urban circuits discussed in the paper, although differences in the influence under the unigrounded and multigrounded conditions may not be as great.

The studies of the committee have disclosed no new co-ordinative measures which may be applied to rural power and telephone circuits but indicate that certain of the measures outlined in the Coleman-Davis paper are applicable in rural areas. Since the ground-return charging current components are of particular interest, measures which tend to limit their magnitudes are relatively more important than those which primarily affect the transformer exciting current or load current components.

Experience has shown that the magnitudes of the charging currents may be affected in either the unigrounded or multigrounded cases by resonant conditions and propagation effects which occur in the longer circuits used in rural areas. The importance of these effects depends upon the voltage wave shape impressed on the circuit. The charging currents may therefore be reduced by improvement in the wave-shape conditions. The ground-return components of the charging currents on 3-phase lines may also be reduced by maintaining the greatest practicable degree of balance-to-ground of the system, by equalizing the lengths of single-phase extensions connected to each phase.

Since most of the rural telephone plant is of open-wire construction, the use of adequately co-ordinated telephone transpositions and the avoidance of severe unbalances in the open-wire conductors may often be a practicable and effective co-ordinative measure.

The method of co-operative planning of routes by both parties to avoid severe exposure conditions, which has been found effective in urban areas, is sometimes more difficult to employ in planning rural extensions, since the power and telephone circuits frequently must be carried along the same highways. Therefore, co-operative advance planning must usually be directed toward limiting the influence of the power system and the susceptiveness of the telephone system.

The paper points out that in many cases desirable magnetic shielding effects may be obtained by grounding the sheaths of exposed telephone cables. The joint subcommittee has found from tests in 2 urban areas that such grounds may often be practicably provided by bonding the cable sheath to the multigrounded neutral of the power-distribution system. Since the neutrals in these urban areas were very well grounded the degree of shielding so obtained was found to be comparable to that observed with other low-impedance grounds.

J. J. Smith (General Electric Company, Schenectady, N. Y.): This paper illustrates well the benefits to be derived from co-operative studies by power and telephone engineers of the mutual problems which arise between their respective systems. My recollection is that in the days when the use of the common-neutral system was first considered on a large scale, some engineers thought that it would considerably increase the influence of power circuits on paralleling telephone systems while other engineers felt that it would not. In order to arrive at the facts, experimental studies were undertaken which over the succeeding years brought forth the results given in this paper. The results described indicate that while the use of the common-neutral system without any reference to inductive co-ordination might give rise to noise difficulties, these can largely be avoided by co-operative procedure with regard to certain features of both the power and communication systems.

The experimental studies led to the breaking down of the over-all noise into its component parts. The tables given in the paper show well the effects of the wave shape of the power system and of the unbalances on the telephone system. The section on inductive coupling, however, refers only to factors which generally influence the type of construction used, whether the systems use the same pole jointly or are at highway separation. I feel that a table or curve giving a comparison of the effects of these types of construction in an average case would be a worthwhile addition to the paper. I should also like to suggest the inclusion in the paper of a comparison of open-wire and cable telephone circuits showing the results to be expected on each in some typical average case.

At the bottom of page 24 it is stated that "direct metallic-circuit induction can be greatly reduced by systematic transpositions in the telephone circuit." This agrees with the results in table 9 where variations of 5 to 1 up to 20 to 1 are given for the contributions to the noise from open-wire sections. These variations are attributed to the effectiveness of the transpositions. On page 24, however, the further statement is made that "due to the physical limitations in a practical layout of telephone transpositions the reduction in metallic-circuit induction is on the average from 60 to 80 per cent on nonpole pairs and about 90 per cent on pole pairs." These reductions, ranging from 2 to 1 up to 5 to 1, do not seem to agree very well with the previous statement or with the result given in table 9. I should like to have the authors clarify this point.

Coleman and Davis: On the first page of the paper reference is made to the start of this system in Minneapolis. Although this was the first extensive use in this country the system was developed and installed in Toronto, Canada by Mr. Hood prior to its installation in Minneapolis.

Mr. Smith raises 2 technical points that appear to require slight elaboration to answer.

Effectiveness of transpositions in exchange lines cited on page 24 are average values based on tests made by the joint subcommittee on development and research on several lines and published in volume 2 of "Engineering Reports," table IX, page 102. Under favorable conditions greater effectiveness than the average can of course be obtained. In table IX, page 25, the lower values of the noise contributed by the open wire is for a transposed nonpole pair and the higher value is for a nontransposed pair. Consequently the range shown is greater than that obtaining for a particular pair when transposed and nontransposed.

"Engineering Reports" 13 and 17, (volume II and III) show complete information on coupling and since there are many factors such as direct metallic and longitudinal coupling for both the balanced and residual components of both current and voltage each varying differently with separation it does not seem feasible to prepare a summary curve.

For distribution circuits induction from residual currents and voltages is frequently the controlling factor. The table I shows the order of magnitude of the ratios between joint use and roadway separation for residual coupling.

Table I

Type of Telephone Construction	Component of Noise	Relative Noise: Joint Use About 6 Feet Separation	40 Feet Separation	75 Feet Separation
Open wire	Direct Metallic			
	1. From voltages	100	20	7
	2. From currents	100	20	12
	Longitudinal			
	1. From voltages	100	28	12
	2. From currents	100	54	39
Cable	Direct Metallic		Negligible	
	Longitudinal			
	1. From voltages†		Negligible	
	2. From currents†	100 approximately	54	39

† Assuming cable sheath grounded at one point only.

Calorimetric Measurement of Dielectric Losses in Solids

Discussion and authors' closure of a paper by H. H. Race and S. C. Leonard published in the December 1936 issue, pages 1347–56, and presented for oral discussion at the communication session of the winter convention New York, N. Y., January 25, 1937.

P. M. Lincoln (Cornell University, Ithaca, N. Y.): The paper by Messrs. H. H. Race and S. C. Leonard, describing calorimetric measurement of dielectric losses in solids is an interesting one.

The general theory of the procedure is perfectly sound. This theory is that a certain known power applied to a given mass of material during a given time will raise that material to a certain determinable temperature at the end of that time. The temperature at the end of the power application is inferred from the cooling rate, details of which are fully described in the paper. If then power is applied to a similar mass of material at an unknown rate, the power can

be inferred by determining the temperature elevation after a given short time.

The method is perfectly sound in theory, but there are a number of discrepancies which appear in the data submitted in this paper which I believe deserve further explanation.

In the first place the points at which the wattage is applied to the samples under test, and to the calibrating sample are quite different. In the test samples the wattage is applied presumably at a uniform rate throughout the mass of the material. In the calibrating sample, however, the wattage is applied to the exterior surface of the sample, and it is an open question whether or not the temperatures measured by the method indicated are a true relative measure of the energy input in the 2 cases. In the case of the calibrating sample there must necessarily be a flow of heat from the point of generation to the point of measurement, and it is highly questionable whether or not the heat is uniformly distributed throughout the sample at the end of the short time of the calibration sample test run.

The method of measuring temperature of both the calibrating sample and the test sample is such that it gives essentially the temperature gradient at the surface of the piece under test. This temperature gradient is in turn a measure of the cooling rate. One of the things in this paper, for which I see no explanation, is the decided difference in the cooling rate for the calibration sample, as compared to the test sample which presumably is identical in every respect, except that the calibration sample is covered with a thin coating of conducting material. An analysis of figure 8, for instance, showing the cooling curves taken during the d-c calibration on the fused-quartz calibration sample, shows that the rate of cooling is such that the temperature falls to $^1/_2$ the initial temperature in approximately 100 seconds as a minimum and 150 seconds as a maximum. These cooling rates are shown by the slope of the cooling curves. The slopes of all curves in figure 8 are not the same. The slope of the curve starting at the maximum temperature is approximately 50 per cent greater than that of the curve which starts at the minimum temperature. This is as might be expected, since it is well known that the rate of cooling due to natural convection decreases with temperature elevation, and the above result might have been anticipated. However, when we come to compare the rates of cooling shown in figure 8 on the calibration sample, with the rates shown in figure 13 on a test sample, which is presumably a duplicate of the sample of figure 8 except that it has no surface conductor, we find a rate of cooling entirely different. In figure 13 the rate of cooling is such that $^1/_2$ the initial temperature is reached in from 220 to 250 seconds, or, in other words, the rate of cooling is only about $^1/_2$ of what we find on the calibration sample. I should like to ask Mr. Race if there is any known reason for this rather remarkable difference in the cooling rates of the 2 presumably duplicate samples.

If now we compare figure 10, which shows the cooling curves of the Isolantite calibration sample, with those of figure 14 which shows the cooling curves for test sample of the same material, we find that a very similar condition exists. In figure 10 $^1/_2$ of the initial temperature is reached in 75 to 110 seconds, while in figure 14 we find that it requires 130–150 seconds to arrive at $^1/_2$ the initial temperature. Why should there be this difference?

If I may be permitted, I should like to suggest one possible explanation for these discrepancies. It is quite possible that the temperature of the rather heavy masses at the ends of the samples under test was quite different during the test upon the calibration sample, and the test upon the test sample. Analysis will show that a very considerable portion of the heat applied to these samples will escape by thermal conduction, and of course the rate of heat escape by thermal conduction will depend upon temperature difference between the rather heavy metallic terminals on the samples and the temperature at the midpoint of the sample. I do not find that Mr. Race made any attempt to determine the temperature of these terminals. I am informed by those more familiar with high-frequency radio matters than I, that there is a possibility during the application of the high voltage, high frequency test, that some heat will be developed in the rather heavy terminals on the test sample. If this is the case, it would explain the difference in cooling rates that I have pointed out above.

If, as I suspect, a very considerable part of the heat in both the calibrating and the test samples is carried away by thermal conduction, the question of thermal conductivity of the materials under test will have a very decided bearing upon the results attained. Thermal conductivity of materials such as Mr. Race is experimenting with, varies over a very wide range. For instance, reference to the Smithsonion Physical Tables, confirmed by the International Critical Tables, give values as follows:

For crystalline quartz perpendicular to axis of 0 degrees centigrade

$k_t = 0.0173$

For crystalline quartz parallel to axis, same temperature, the value of k is 0.0325. For hard rubber at 0 degrees centigrade the value of k is 0.00037, being thus about 1 per cent of that for crystalline quartz. I can find no values of this constant for fused quartz, but I understand it to be of the order of 10 per cent or 15 per cent of that of crystalline quartz.

For Isolantite the value of k is 0.00175. It will thus be noted that the thermal conductivity of the materials which were tested by Mr. Race vary over a very wide range. For instance, crystalline quartz parallel to the axis has a thermal conductivity, which is approximately $3^1/_2$ per cent of copper, while hard rubber has only about 0.04 per cent of that of copper, a variation of nearly 100 to 1. If, as I suspect, there is an appreciable dissipation of heat by thermal conduction during the 2 minute application of high potential, high frequency, to the test samples, will not this variation in thermal conductivity lead to results which are far from accurate?

The methods which Mr. Race is proposing in this paper certainly are interesting, and are worthy of additional study, but I would question whether the results so far obtained are of a very high degree of accuracy. I believe that if Mr. Race had taken his cooling curves between the center of his sample and the metallic terminals thereof his results might have led to determinations quite different from those cited in his paper.

There is one other point that might be mentioned before closing this discussion. If the information which I have received is correct, namely, that heat is developed in the metallic terminals during the high-potential high-frequency voltage application, this very fact would cause the results as reported in the paper to be quite erroneous. I should like to inquire whether or not any tests have been made to determine if there is such a loss in the metallic terminals during the period of high-potential high-frequency application.

C. L. Dawes (Harvard University, Cambridge, Mass.): To my mind the authors have developed a new and valuable technique in the methods of measuring dielectric losses. It permits measurement of such losses at high voltages simultaneously with high frequencies, which would otherwise be quite difficult. Also, because of the rapidity with which measurements can be made, the method is valuable not only for control work but for the rapid comparison of different dielectric materials. In the method as it has so far been developed, there are some possible sources of error. In figures 8 and 10, which give the cooling curve for the calibrating samples with fused quartz and Isolantite, the rate of cooling is much greater than with the test samples, as given by figures 13 and 14. This is explained, I believe, by the fact that with the calibrating samples the power is applied only to the surface. On cooling, some of the heat flows inward toward the center, thus producing a more rapid rate of cooling than with the test sample. With the latter, heat is produced throughout the body of the sample and the heat flow must necessarily be outward toward the surface. This gives a lesser rate of surface cooling than for the calibrating sample. Also it is questionable whether or not the placing of the thermocouple on the surface of the sample not covered by the surface layer of resistor material gives a true criterion of the cooling of the calibrating sample itself. Heat must flow over more or less irregular paths from the heated surface to the point of contact of the thermocouple. To my mind, these 2 difficulties might be overcome by calibrating with steady-state measurements, using the method of Baldwin.

Moreover, in calorimetric measurements the losses over the surface as well as the internal losses of the sample are measured. That is, surface losses cannot be eliminated by the usual guard electrodes, as in electrical measurements. Also the potential difference is applied between the 2 ends of a sample the length of which is considerable in comparison with the diameter. Hence the field between the electrodes will not be uniform and the dielectric lines will diverge outward as they leave the electrodes. This makes the stress per unit volume less at the midzone of the sample than at the ends. Hence the loss per unit volume throughout the sample is not constant. This, however, probably would have little or no effect so far as the comparison of samples of similar geometry is concerned.

The authors have attempted a very difficult problem and in their first attempt may not be expected to have brought the method

to perfection. They should be complimented on having obtained such rational results under very critical and difficult conditions.

L. A. Burckmyer, Jr. (Cornell University, Ithaca, N. Y.): This paper is very outstanding in its clear and full presentation of the test data. However the authors seem to have given only a small amount of attention to the interpretation of these data.

There is evidence that temperature conditions were not governed by the simple heat-storage relations that the authors relied on in determining the loss of a sample by the use of a calibrating resistor of different material. Thus equation 4 states, in effect, that the quartz calibrating resistor requires 0.25 watts (per cubic centimeter) per degree per calorie per cubic centimeter, on a 120-second test, or 30 watt-seconds per calorie, instead of 4.186, or the temperature difference ΔT_0 is about $^1/_7$ the temperature rise that would occur with no heat loss.

There are 2 possible explanations:

(*a*). The values ΔT_0 do not represent actual temperature rise, or
(*b*). The heat lost plays a very important part in the temperature attained.

Both of these are true, as can be shown by analysis of the cooling curves of, say, the quartz calibrating resistor. The uppermost curve (figure 8) shows a thermal time constant of about 150 seconds, indicating a heat loss which should have resulted in a temperature rise of about 2 degrees, or about 5 times ΔT_0, during the heating period. (With no heat loss, the rise would be about 3 degrees.)

In view of the construction of the apparatus, it would not be unreasonable to assume that ΔT_0 represents only about $^1/_5$ the actual rise, but to justify extrapolation of the cooling curves by drawing them as straight lines it is essential that ΔT_0 be a *constant* fraction of the true rise. However, the slopes of the cooling curves on the quartz calibrating resistor differ by as much as 1.6 to one, and the average of these is about twice as great as the slope of the cooling curves on the quartz test sample, raising a question as to the significance of the results even when the calibrator and sample are made of the same material. As it is unreasonable to ascribe these variations to inconstant coefficients of heat transfer over the narrow range of working temperatures, it seems likely that ΔT_0 does not even represent a fixed fraction of the true temperature rise; or, in other words, that the assumption of a linear cooling curve is arbitrary and unjustified.

The heat loss of the quartz calibrating resistor is about 6 times as large as can be accounted for by even black-body radiation. This discrepancy persists for any assumed ratio of actual temperature rise to ΔT_0. Hence the temperatures must have been controlled largely by conduction, presumably to the massive metallic end pieces. If this is so, the inferred losses on all materials other than fused quartz and Isolantite can have little significance, for the conduction effects were not taken into account and would be entirely different in the calibrating resistor and in the test sample.

In the absence of any published defense of the construction of the calibrating resistor, with its surface heating and with temperature measurement made at the middle of a bare $^1/_4$-inch strip, any close agreement between the thermal behavior of the calibrating resistor and the test sample must be regarded as a fortunate accident. Certainly conduction plays a part in the heating of the bare strip, and it seems incredible that a radical change in the width of this strip would not have materially affected the calibration data.

With elimination of conduction effects and with a calibrating resistor that simulates the test specimen in all essential respects, it is likely that this method would be capable of yielding accurate results in measurements on dielectrics.

H. H. Race and **S. C. Leonard**: Before answering specific questions raised regarding this paper, we should like to make this general comment: The ranges of voltage and frequency over which bridge and substitution measurements can be used to measure dielectric constant and dielectric loss of solid insulating materials is shown in figure 1. Such methods cannot be used at high voltage high frequency, whereas calorimetric methods should be possible at frequencies and voltages equal to or higher than those we have used if a measurable power supply is available. The major disadvantage of previous calorimetric methods has been the time required to reach steady state. This paper reports progress in a 3 months attempt to use a transient calorimeter in this hitherto unexplored field of loss measurements on solid dielectrics. There is need for further refinement of the method which was presented with the hope of stimulating other workers to try transient calorimetry.

Specific questions can be separated into 3 classes:

(A). Thermal Conduction From the Ends of the Samples

When we started this work we planned to use samples 6 inches long with the hope that axial conduction would have a negligible effect upon the temperature of the midpoint. Our first measurements showed that with the maximum voltage available the gradient in long samples of low-loss material was insufficient to produce a measurable temperature difference. Therefore the samples were shortened to $1^1/_2$ and 2 inches with recognized attendant increases in the effects of axial thermal conduction. Preliminary calculations from the experimental data showed that about 80 to 85 per cent of the heat generated during a 2-minute heating period was being dissipated through the metal electrodes. Therefore, the theoretical thermal characteristics of our specific calorimeter were calculated by Doctor H. Poritsky of our engineering general department.

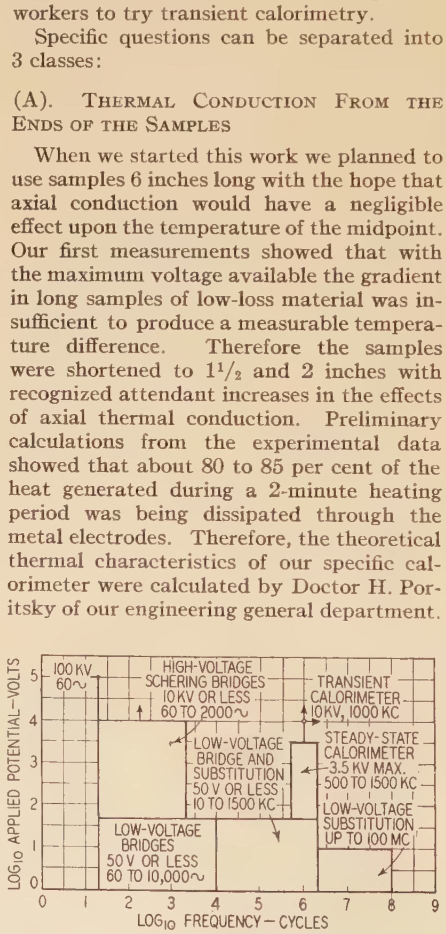


Figure 1. Loss measurements, solid dielectrics

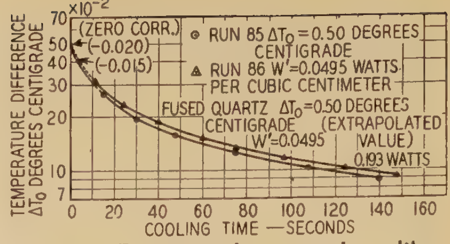


Figure 2. Transient calorimeter d-c calibration with solid carborundum resistor; 2-minute runs

His results indicated that (*a*) *assuming zero end conduction, the time constant of radial convection and radiation should be* about 725 seconds, and (*b*) *assuming the metal ends to be infinite heat sumps, the time constant of axial conduction should be about 150 seconds.* This latter value is of the same order as the measured time constants, indicating that the major portion of the heat is being dissipated axially. Because of space limitation, these mathematical studies of heat flow could not be included in the paper, but are available in report form. The fact that a major portion of the heat is dissipated axially should not prevent the use of the differential thermocouple to measure total heat if the thermal circuits have constant coefficients and if the test piece and calibrator are made of the same materials. When the test piece and calibrator are not of the same material the estimation of total heat is certainly less accurate.

(B). Time Function of Temperature Relaxation

We have not used the time constants of the temperature measurements to indicate heat generated, but have extrapolated the data to the time of removal of potential to obtain ΔT_0. We have observed that the time constant of temperature relaxation changes with experimental conditions and that if the ambient temperature is changing the relaxation curves may not have the same slope or may not be exponential in form, however, we found that the extrapolated values of ΔT_0 are effected much less than the time constants by such changes in ambient conditions. Considerable more work must be done to determine the ultimate accuracy of this method. The paper shows the check obtained for the absolute value of loss factor of fused quartz.

(C). Type of Calibrator

Since thermal conductivity of a sample is important, it was considered necessary to make the calibrator of the same material as the test piece or of a material having comparable thermal conductivity. No materials are available having sufficiently high volume electrical conductivity so that they could be used as calibrators which also have the same thermal properties as the materials being tested. A one-point calibration was obtained using a solid carborundum calibrator as shown in figure 2. The cooling curves were not exponential functions and the steepness of the initial slopes caused by its greater thermal conductivity made it difficult to determine the extrapolated value of ΔT_0. Variations as great as 30 per cent could be made in this extrapolation. The value of ΔT_0 as extrapolated in figure 2 when corrected for specific heat and density

agreed with the value of ΔT_0 obtained from the fused quartz calibration curve for the same value of watts per cubic centimeter input.

Since the surface type calibrators gave more consistent data, we asked Doctor Poritsky to make a mathematical analysis of the temperature rise at the center of the uncoated portion assuming uniform heat input to the remaining surface and zero heat loss. The mathematics are too involved to be included here, but indicated a heat rise at this point of 2.8 degrees centigrade for a total heat input of 0.2 watts for 2 minutes. Likewise, if we assume uniform volume heating at 0.2 watts for 2 minutes and zero heat loss the average temperature rise should be 3.0 degrees centigrade. Therefore, the error resulting from surface heating is given by the ratio of 2.8 to 3.0 degrees centigrade. On the other hand we have already shown that heat dissipation to the ends is a much more important factor. This is again indicated by the fact that the measured value of ΔT_0 was only 0.42 degrees centigrade for these conditions.

Whether or not this ratio of 0.42 to 2.8 remains constant is one of the important factors to be investigated more thoroughly. The independent check obtained in the case of fused quartz and the fact that measurements on other low-loss samples give consistent results between different samples of similar materials and yield loss factors of the order of magnitude anticipated indicates that the variation in this ratio may not be as serious as has been assumed.

Case II under "Calculations" was presented as a possible method of determining a value for loss factor for a material that was different from that of the calibrating body. Calibrators were made of several different bodies other than the quartz and Isolantite units described in the paper and correlation of the experimental data thus obtained led to the presentation of case II. We realize that this method is based on a limited amount of experimental data and that case I is the preferable method.

On the whole we are pleased with the initial results obtained with the transient calorimeter as reported in this paper. The complete development of a measuring technique built around this method obviously will require a large variety of samples. In the meantime we believe that with adequate manipulation and analysis that satisfactory results are obtainable.

Automatic Boosters on Distribution Circuits

Discussion and author's closure of a paper by Leonard M. Olmsted published in the October 1936 issue, pages 1083–96, and presented for oral discussion at the power distribution session of the winter convention, New York, N. Y., January 26, 1937.

J. A. Brooks (New York and Queens Electric Light and Power Company, Flushing, N. Y.): The author has discussed in detail the application of automatic step boosters on 4-kv distribution feeders. I am inclined to agree with his views in the case of most rural circuits. That is, I feel that an automatic booster controlled by voltage relays is the solution to low-voltage problems where neither the feeder nor the bus to which the feeder is connected are regulated. In such a case, the voltage on the feeder is determined not only by the load on the feeder but by external conditions quite remote from the feeder itself. As a consequence, the feeder voltage is likely to have a large spread and voltage control for the booster must necessarily be the choice.

However, in the cases which the author describes, where the feeder voltage is held substantially constant at some feed point by induction regulators in the station, it appears to me that the possibility of current control for the boosters has been dismissed too lightly. The author states that current control operates on the principle that the voltage drop in the line is directly proportional to the current flowing. Actually, of course, the voltage drop depends upon 3 factors, they are: (1) The impedance of the circuit; (2) the current flowing in the circuit, and (3) the power factor of this load current. Of these 3 factors, the circuit impedance is a known constant and I submit that, for a circuit which feeds a suburban load, the power factor is also a constant for any given time of the day. With these 2 factors constant the only variable remaining is the load current. In my opinion, therefore, the assumption on which current control is based is accurate.

In the case which the author cites for a $2^1/_2$ per cent single step booster controlled by voltage relays it is shown that, due to an expected one per cent error in relay accuracy the effective boost obtained is only 1.5 per cent. This amounts to a reduction of 40 per cent in terms of the booster rating. If current control were used in this case and the relay error was the same—one per cent—the effective boost would be lowered by only one per cent of the voltage drop. Since the booster rating will be of the order of magnitude of the voltage drop, the relay error would result in a reduction in booster effectiveness of only one per cent in terms of the booster rating or one fortieth of that when voltage control was used.

P. E. Benner (General Electric Company, Schenectady, N. Y.): Mr. Olmsted has made a very interesting analysis of the application of boosters to the distribution circuits of the Duquesne Light Company. It should be noted that his particular problem was not one of economically regulating small loads and low-capacity feeders but consisted of supplementing the regulation of the feeder induction regulators at the substation. In this connection it would be well to differentiate between the low-capacity low-cost 10-per cent-range regulator and the low-range supplementary booster used in connection with the usual station-type feeder regulator. As shown by figure 1 the pole-type induction regulator and the small 4-step regulator were developed to make it possible to economically regulate small loads and low-capacity circuits. By means of these regulators, capacities as low as 10-kva can be obtained at approximately the same cost per kilovolt-ampere as the larger station-type regulators.

The booster on the other hand is strictly a supplementary device. A one-step booster can be readily arranged to give one $2^1/_2$-per cent fixed boost and one $2^1/_2$-per cent automatic boost. By following through the author's method of analysis, it will be seen that this arrangement gives exactly the same results as a booster having 2 automatic steps because theoretically the first step is always in. Therefore, there is no particular advantage in having the first step automatic. Moreover, the one step device lends itself to a much simpler control and should be especially attractive for this reason. Figure 2 shows several curves similar to those plotted in the author's figure 6. The curve on the one $2^1/_2$-per cent fixed and one $2^1/_2$-per cent automatic step booster has been extended to cover the same range as the 2—$2^1/_2$-step booster inasmuch as the analysis shows it will produce the same results. It will be noted that the curves have been terminated so as to indicate the useful range of the device in question. Extending the curves horizontally to the right-hand margin might easily give the impression that the device was economically applicable for the entire variation of primary voltage, whereas it is believed that it would be very questionable to say the least to use a device which did not make full use of the permissible primary-voltage variation.

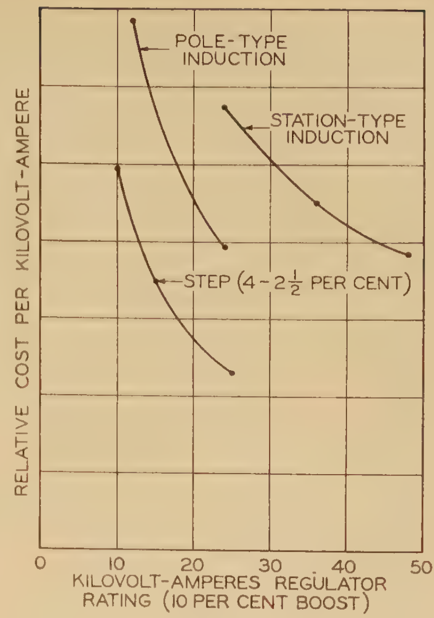


Figure 1

It is believed that further consideration should be given to the analysis by which the author concluded that the 2—1.33-per cent step booster would give the most economical operation for a primary voltage variation of 5 per cent. Figure 3 shows the factors entering into this analysis. The primary voltage varies from 100 per cent to 105 per cent. The booster is selected on the basis that its range plus the band width of its control is equal to 5 per cent. As shown, the band width figures to be plus or minus 1.17 per cent and the range 2.66 per cent. It will be noted that at full load when the incoming primary voltage is 100 per cent, the booster would attempt to hold the outgoing primary voltage within the band width for which the control was adjusted. Ordinarily the voltage held would average somewhere near the center of the band-width setting. However, in this case because of the limited range the maximum voltage which could be held approximates the lower limit of the

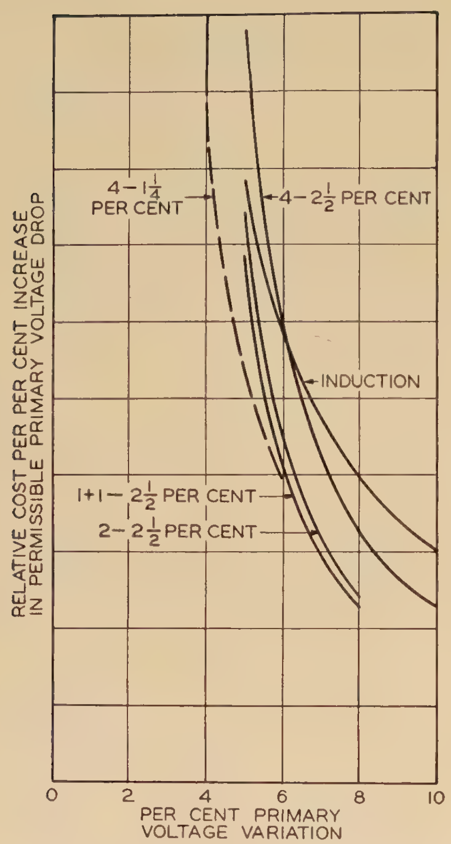


Figure 2

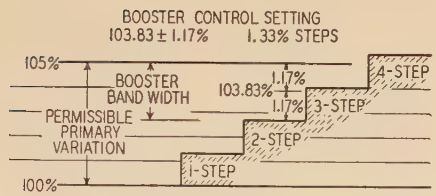


Figure 3

band which is a full one per cent lower than would be held if the booster had an additional one or 2 steps. It is believed that this extra one per cent in outgoing voltage is easily worth the extra cost of the larger range device. Referred to the cost of the device itself, if the first 2 steps is represented by 100 per cent the next 2 could be had for approximately an additional 30 per cent. In other words 2 additional steps, one of which as shown by the analysis would be in service at full load, would cost only about 60 per cent as much as each of the first 2 steps.

In view of this analysis it is believed that from the theoretical as well as the practical standpoint rule number 2 governing the selection of boosters should be changed to read, "The voltage range of the booster should be approximately the same as the permissible primary voltage variation in order to allow the booster to hold the maximum voltage possible."

The author has admittedly been conservative in regard to the amount of primary voltage variation permissible. It can be readily seen that the 5 per cent variation used in the analysis could easily be extended to $7^1/_2$ per cent by assuming the difference in drop between the heaviest and lightest loaded transformers and secondaries to be $2^1/_2$ per cent instead of 5 per cent. It should be noted that line-drop compensation would be necessary to take advantage of this increase in range from 5 per cent to $7^1/_2$ per cent. That is, the booster or regulating device would hold voltage not at the point where it was located, but it would compensate for a portion of the distribution transformer and secondary drop.

From a practical standpoint it is obviously desirable wherever possible to use a regulator or booster having a range and size of step applicable to average rather than specific feeder conditions in order to permit a degree of standardization which will justify the low price levels desired on this type of equipment.

L. H. Hill (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): Mr. Olmsted is to be congratulated on having presented a paper which includes considerably more fundametal data than would be indicated by the title of his paper. Ever since the introduction of step voltage regulators, there has been considerable discussion concerning the use of time delay in the control; and Mr. Olmsted shows conclusively that the use of time delay will give good results from a regulation point of view. He also considers the effect of primary relay setting on the number of operations and also the size of step that can be used. His analysis of the effect of size of step on the range of regulation is general and would apply to any type of regulator.

It might be pointed out in connection with figure 5 that since Mr. Olmsted's conclusions are drawn on the basis of a regulator with 5-per cent range, the 8-step regulator would provide a $^5/_8$-per cent step instead of a $1^1/_4$-per cent step for this application, in which case the relative effectiveness curve would have been above the curve for the induction regulator.

Naturally since Mr. Olmsted's conclusions are based on a total of 5 per cent regulation, it is necessary to point out that other conclusions might be reached for regulators of the conventional 10-per cent range, such as are needed on more rural-type lines.

It should also be pointed out in connection with figure 6 concerning the relative costs of various automatic voltage boosters the conclusion might be drawn that the size of step were the only variable. As a matter of fact, these costs must be based on equipments made by different manufacturers, and it cannot be assumed that the cost of the various mechanisms is comparable. Actually, there is considerable difference in the quality of mechanism in booster regulators of various steps. There seems to be an impression abroad on the part of some designers—and also operators, for that matter—that the tap-changing mechanism in a branch feeder regulator can be something light and flimsy, simply because it is used for branch regulation. It might be admitted for sake of argument that a regulator on branch service may not operate as frequently as one used for station type service; however, the branch type regulator will undoubtedly operate for much longer periods of time without inspection. The very nature of the application—mounted on poles in more or less inaccessible places—means that inspection and maintenance will be at a minimum; and it will not be unreasonable to expect that branch feeder regulators in many cases will operate for long periods of time without any inspection or maintenance whatever. Accordingly, it is my opinion that the mechanisms used in branch feeder regulators must be of the same order of quality as the tap changing mechanisms used in station-type regulators.

L. M. Olmsted: Before replying to the discussions, I wish to correct 2 errors in the published article. In figure 8, the per cent regulation from B to C should be 3.00 per cent instead of 2.66 per cent. In table II, the relay-band widths should read ± 1.00, ± 1.10, ± 1.25 and ± 1.38. It is well to observe also that table II presents estimated data and that a series of experiments intended to check them is under way but not yet completed.

I agree with Mr. Brooks' statement that voltage drop in a distribution feeder depends upon (1) impedance of the circuit, (2) current flowing in the circuit, and (3) power factor of the current. It must be observed, however, that the purpose of a booster on a regulated feeder is to correct for voltage drop between the feeding point and the booster. If there is no load tapped off the circuit between these points, then the current through the booster provides a fairly accurate measure of this voltage drop and could be used to control the booster. Usually most of the load is fed from the circuit between the feeding point and the booster, however, and a considerable part of the voltage drop is caused by load current which does not pass through the booster. In such cases the current through the booster is not an accurate measure of the voltage drop and could be used to control the booster only if the characteristics of loading on the circuit are such that the current flowing through the booster is always proportional to the voltage drop between the feeding point and the booster. For example, assume a circuit passing through an industrial section and into a residential area; voltage is low in the residential area and a current-controlled booster is installed between the 2 areas to correct it. With the relay adjusted to give satisfactory night-time voltage, the residential area might continue to get low voltage during the daytime because its day load might be too light to operate the booster to correct for the voltage drop caused by the low-power factor day-time industrial load between the feeding point and the booster.

It is quite true that the great spread between light-load current requiring no boost and heavy-load current requiring boost might permit a relay setting which would sacrifice less than one per cent of the circuit voltage, but the necessity to allow for disproportionality between booster current and voltage drop could very easily eradicate this advantage. Such considerations led the author to write that "the accuracy with which the voltage is regulated (by current control) depends upon the consistency with which the distribution of load along the circuit is duplicated from day to day. This limitation is overcome by voltage control.. ...."

Mr. Benner has advocated the use of boosters having one permanent step and one automatic step in place of 2 automatic steps. Undoubtedly the first booster on a

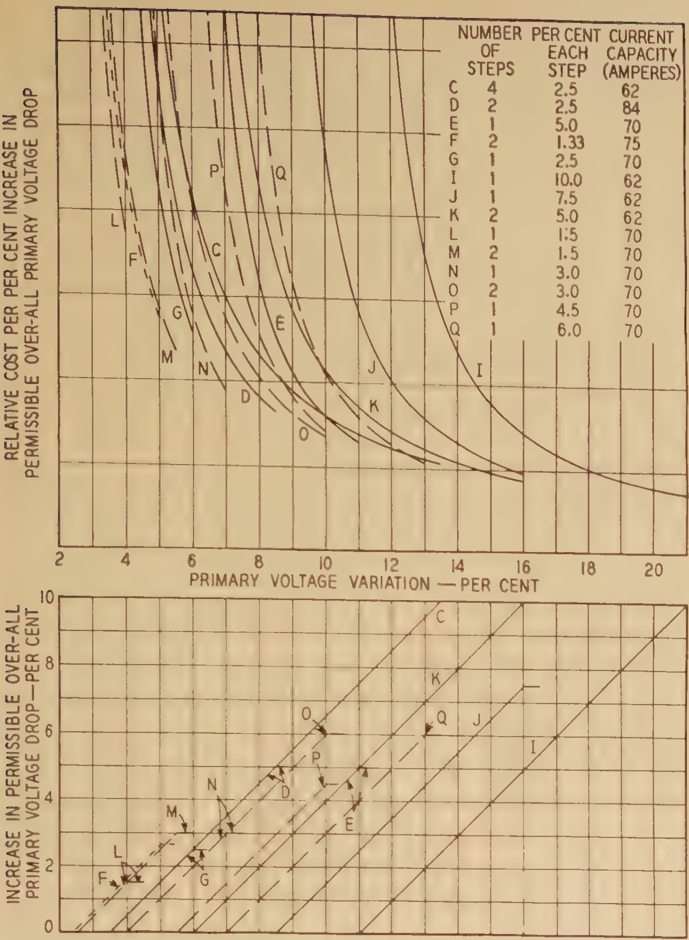


Figure 4

circuit could be of this type, but a second booster in series could not have a fixed step without causing high voltage during light-load periods. A booster having a permanent step cannot be set on neutral and bypassed out of service without interrupting customers beyond the booster. Furthermore, it is difficult to avoid some phase unbalance on long circuits, and a permanent booster might tend to increase the voltage on a phase already high on account of unbalance. The difference in cost is not large, and it is doubtful whether the savings offset the disadvantages.

Mr. Benner's criticism that the limited range of the 2—1.33 per cent step booster results in a full one per cent lower output voltage than could be secured by a 4-step booster is minimized by the fact that the input voltage of 100 per cent, upon which it is founded, actually is the lower limit of a 101 ± 1 per cent voltage band and would exist for comparatively short periods. It is well to note, however, that 4 0.8 per cent steps would hold the output voltage at 104.1 ± 0.9 volts with a lower limit 0.54 volts higher at a relative cost only a little higher than the 2 1.33 per cent steps. Of course 0.8 per cent is not a standard step, but as long as a 4-step regulator with a total range of 5 per cent or less is not standard anyway, I see no reason why the step size should not be selected for the application.

Obviously it is desirable to use a regulator or booster having a range and size of step applicable to average rather than specific feeder conditions. The very fact that these standard ratings have been found so grossly inadequate for applications having limits admittedly close but not unusual leads one to wonder whether a more generally applicable set of standards might be developed. Mr. Benner has noted that the problem "consisted of supplementing the regulation of the feeder induction regulators at the substation" and that the booster was developed for this purpose. Why, then, was a total range of 10 per cent incorporated into the design? The diagrams show the curves of figures 5 and 6 of the paper (corrected for price changes) extended to show the full range of each device. Note that a primary voltage variation of 21 per cent is necessary to secure the full effectiveness of a 1–10 per cent step booster. Surely so great a variation in primary voltage is excessive for any system. If we limit the primary voltage variation to 14 per cent, which certainly could not be considered too close, we find the 1–10 per cent step booster completely outclassed, both in effectiveness and in relative cost, by the 1–7.5 per cent and the 2–50 per cent step boosters although neither is used to its maximum effectiveness.

Boosters of somewhat less range designed for maximum effectiveness at 14 per cent primary voltage variation would have either 1–6.5 per cent step or 2–4.33 per cent steps and the relative cost, taking the price as that of the corresponding standard ratings, would be from 10 to 18 per cent lower because of the increased effectiveness. Following the present established practice of having taps at the quarter points on the one-step design, and of having a series-parallel connection on the 2-step, we would find steps of 1.62, 3.25, 4.88, and 6.50 per cent on the one and steps of 2.16 and 4.33 per cent on the other. These steps are somewhat more adaptable to the close limitations discussed in the paper than are the steps at present available on standard equipment, and indicate that compromise ratings might be found which would prove entirely satisfactory for both types of application. It is suggested that this compromise rating have 1.5, 3.0, 4.5, and 6.0 per cent taps, with a choice of one-step or 2-step tap changers. People requiring close regulation could use 2–1.5 per cent steps to secure a maximum of 3.0 per cent increase within a primary voltage variation of 5.5 per cent. People requiring maximum correction at minimum cost could use 1–6.0 per cent step to secure an increase of 6.0 per cent within a primary voltage variation of 13.0 per cent. Intermediate requirements could be satisfied by 1–3.0 per cent or 1–4.5 per cent step, or 2–3.0 per cent steps. The dashed curves based upon prices of corresponding capacity in standard ratings, show that these proposed steps lower the relative cost of booster operation within 5.0 per cent limits practically to the 2–1.33 per cent special design, and yet can be applied to the wider limits for which the present standard designs are suitable with no increase in relative cost.

Inasmuch as the amount of boost has been reduced, the largest rating of booster in the 2,400-volt class would be 104 amperes at 6.0 per cent or 15 kva, permitting standardization upon the 3 capacities of 5, 10, and 15 kva in place of the present 4. It is my opinion that such a change would be of decided benefit to the industry.

I agree with Mr. Hill's suggestion that 8–5/8 per cent steps would be more suitable than 8–1¼ per cent for the application discussed in the paper. It would not lower the relative cost as much, however, as the one- and 2-step boosters with a total range of 6.0 per cent. Automatic voltage boosters do not receive the same attention in service as the station-type voltage regulators, consequently must be simple and sturdy, approaching as nearly as possible the reliability of distribution transformers. In my opinion time delay is valuable in that it tends to reduce the number of operations, thereby minimizing wear and increasing the time which can be allowed between inspections. Recently a spot welder has been connected on the single-phase extension of the booster application described in the paper, which varies the primary voltage almost 3 volts, and the time delay has proved very desirable.

Trends in Distribution Overcurrent Protection

Discussion and authors' closure of a paper by G. F. Lincks and P. E. Benner published in the January 1937 issue, pages 138–52, and presented for oral discussion at the power distribution session of the winter convention, New York, N. Y., January 26, 1937.

H. P. Seelye (The Detroit Edison Company, Detroit, Mich.): At several points in this excellent presentation of the subject of co-ordination of overcurrent protection, the authors have mentioned the importance of economic considerations and of the rela-

tive amount of customer outage in determining the proper combination of devices. Some light on these factors has been gained from a recent study of outages on the Detroit Edison system.

The Detroit system is divided into 2 sections in which somewhat different conditions prevail. In the suburban part which includes a large number of smaller cities and towns as well as rural territory, the transformers are radial, that is each serving its own separate length of secondary, and are protected by primary fuse cutouts only. In selecting fuse sizes the emphasis has been placed on service continuity rather than protection to the equipment. The smallest primary fuse used is one of 8-ampere rating. This corresponds fairly well with the minimum of 5 amperes for a 20-to-1 ratio system which the authors of this paper have mentioned as giving proper co-ordination with the larger household fuses. The fuse itself is a cartridge fuse of special Detroit Edison design which has an appreciably greater inverse characteristic than the usual expulsion type shown in the curves of this paper. Over a 3-year period an average of only about 75 transformers per year out of a total of approximately 30,000 transformers have been burned out due to secondary short circuits or overload. This is about $^1/_4$ of one per cent. Of these, 38 per cent were $1^1/_2$ kva; 45 per cent, 5 kva; 15 per cent, 10 kva; 2 per cent, 15 kva; and a negligible amount of larger ones. The proportion between number burned out and total in service for each size is: $1^1/_2$ kva, 0.42 per cent; 5 kva, 0.29 per cent; 10 kva, 0.10 per cent; 15 kva, 0.08 per cent. It is evident that, for this system at least, the ratio of burnouts decreases rapidly with size and most of the burnouts occur on $1^1/_2$- and 5-kva sizes. For 15 kva and above the capacity seems to be large enough to burn off most faults.

An estimate of the cost of replacing and repairing burned-out transformers, compared with the cost of using secondary fuses for increased protection, showed that to accomplish any saving such a fuse must cost less than an amount ranging from 75 cents for a $1^1/_2$-kva down to 35 cents for a 10-kva including incidental material and labor of installation. A study of the curves given in this paper shows that it would be rather difficult with the conventional fuses to get much protection from such a fuse on the smaller transformers. As to the benefit to be gained in service continuity, on this system most of the $1^1/_2$- and 5-kva transformers serve only one customer so the loss of service due to their burnouts is not great. Also, the records available indicate that only about $^1/_2$ of the faults which would blow a secondary fuse, and hence interrupt service, do burn out the transformer, the other half clearing, whereas with fuse protection these would be likely to cause interruption.

In the city of Detroit, transformers are banked, that is, the secondaries tied solidly together and the transformers protected by both primary and secondary fuses in their leads. The paper points out the advantages of banking (page 147) in reducing voltage variations and the emergency duty thrown on any transformer and its protective equipment. It apparently favors the "loose" bank, however, with fuses midway between transformers rather than the solid bank, giving a number of reasons, most of which are not as serious in practice as they appear from a distance. It is true that solid banking requires somewhat more care in design than loose banking—for example, primary rings are quite a necessary accompaniment of large banks—but 30 years successful operation of this scheme in Detroit has shown conclusively that it is economical and effective in decreasing customer outage. Its advantage over the loose bank, in addition to maintaining service in case one transformer develops a fault, is that the capacity of 2 or more adjacent transformers is available to burn off a secondary short whereas, with the loose bank, the intermediate fuses are likely to blow, leaving conditions the same as for a radial system. Although cascading of a whole bank in such a case is a possibility which is frequently mentioned as a serious disadvantage, it actually occurs in relatively few cases.

A careful record of all fuses blown on the Detroit banked system over a period of 18 months, and involving about 20,000 transformers, showed only 5 cases of cascading in banks containing more than 4 transformers and in each of these only one side of the $^{115}/_{230}$-volt secondary was involved. Of the remaining cases, 50 per cent had only 2 transformers in bank, the remaining 50 per cent being about equally divided between those with 3 transformers and those with 4. In nearly all of these, the transformers were small and also usually only one side of the secondary went out. On the whole system, 267 transformers, or about $^9/_{10}$ of one per cent per year were involved in these outages but the actual service outage amounted to only half that in transformer-secondary units or $^{45}/_{100}$ of one per cent. The conclusion is evident that the bigger banks do burn off most of the faults which occur and that the best banks have more than four transformers, although of course it is not always practical to make them. Further study of this record showed that the solid banks allowed about 65 per cent less actual interruption than would probably have been experienced with a radial system, and 50 per cent less than with loose banks. Considering the small banks of 2, 3, or 4 transformers alone, the indications were that the solid bank was at least as good in this regard and probably a little better than either of the other schemes, there being many cases in which only one or two fuses were found blown without any service interruption, even where only two transformers were tied together. Transformer burnouts due to service shorts or overloads in this area are negligible.

This is not intended to disparage the "loose bank," which no doubt has its field. It is wished to emphasize what the authors have indicated in their paper that banking of transformers is an important means of improving protection to service and to point out that solid banking is practical and effective where it can be properly applied.

E. J. Burnham (General Electric Company, Schenectady, N. Y.): The paper by Lincks and Benner brings out facts and information which throw considerable light on the problems of overcurrent protection. By using these facts and studying the results much can be gained from the standpoint of the user and fromthe standpoint of the manufacturer.

Being somewhat familiar with the work which the New York Power and Light Corporation has done and is doing along the lines suggested in this paper, the following comments may be in order. Over the past 2 years this company has put in much hard work and effort studying their distribution system by districts to find ways and means of improving service to customers and doing it economically.

In studying a district the plan has been to first inspect the lines and make recommendations as to putting them into first class physical shape. This would include tree trimming where desirable, and seeing that crossarms, braces, and equipment on the poles were installed properly.

Secondly, decision would be made as to the type, rating, and location of overcurrent devices for each circuit in a district. This would usually mean several changes and some additional devices. Time-current characteristics were plotted for the fuses and devices, in manner shown in the authors' paper. Selections were made only after it was reasonably certain as shown by the curves plotted, that no fuse blowing would cause damage to another fuse or incorrectly cause a relay to operate and thereby trip a circuit unnecessarily.

This program has now been carried out over considerable time with what seems to be about 100 per cent results. In some of the long rural lines as many as 4 fuses have been placed in series. These might be rated for example—15, 25, 40, and 50 amperes. Some of the longer lines have been operating this way for about one year with good results as reported from the districts. However, steps are now being taken to improve the way of obtaining and reporting operating results to make sure the fuses and overcurrent devices are operating as expected. It is also the plan to obtain more information regarding the ratio of permanent to temporary faults for different circuits so the benefits to be derived from the use of reclosing devices may be determined. This seems to be a step in the right direction, because if it is worth while to spend much time and effort selecting and applying fuses and overcurrent devices, it certainly is worth while to get complete outage data and then analyze it to determine if the devices are operating as expected and also determine if any improvements can be made in the devices themselves or in the ways of using them.

R. H. Earle (Line Material Company, South Milwaukee, Wis.): There is a certain type of low-cost rural system now being built in different parts of the country which probably includes more of the interesting problems described by Messrs. Lincks and Benner than any other type of power distribution.

I refer to those systems in which power is delivered to individual farms through $1^1/_2$- or 3-kva transformers supplied by 4,800-volt or 6,900-volt single-phase grounded branch lines or subbranch lines. At the customer's service entrance 60-ampere fuse boxes are provided. The transformers have internal fuses and have spill-over gaps instead of lightning arresters. All branch lines have repeater fuses or reclosing breakers where the line branches off from the main feeder. When one of the gaps flashes over due to lightning the branch-line

fuse blows to clear the circuit. After a momentary interruption the next fuse of the repeater comes into the circuit and power is restored.

The 60-ampere fuse which it is possible for the customer to insert in the service box is considerably oversize for the initial load, which the customer is expected to provide and this 60-ampere fuse is, of course, too large to afford much overload protection to the transformer. The likelihood of this load increasing, however, warrants the large service fuse although first cost prohibits the installation of a larger transformer.

If the transformer fuse is installed inside the tank, it is important that the fuse co-ordinate with the 60-ampere secondary fuse and that it blow only in case of dire necessity because of the inconvenience of replacing the link. As a result the size of this link is selected so as to blow in case of a short circuit between service wires leading to the customer's house but to let the 60-ampere secondary fuse take care of less serious trouble.

The spill-over gaps that are used instead of lightning arresters require the system to be broken up into as small sections as possible so that when one of these gaps flashes over and blows a branch line fuse, only a few customers will be affected. This sectionalizing requires that the fuse links on the various branches and subbranches be spaced closer together than is ordinarily permissible. The result is that certain values of fault current will blow not only the nearest fuse but will also take out the next larger fuse in the series. A larger number of customers are affected than is entirely desirable, but since all fuses are of the repeater type the interruption of service is momentary.

A system of this kind obviously makes certain sacrifices in quality of service in order to reduce the cost of the lines to a point where it is possible to build them, and is a good example of the increasing demand being made on fuses for greater accuracy in co-ordination.

G. B. Dodds (Duquesne Light Company, Pittsburgh, Pa.): The authors have correlated a great amount of information relative to the protection of distribution circuits. The information they have obtained regarding outage data of various companies is particularly interesting.

As the authors have pointed out, there is a wide variation between the companies in the frequency and nature of outages. However, in one respect there is a disappointing similarity. This is in regard to the permanent line outages (per 100 miles of line) as shown in line 1, table II. Although the numbers vary greatly for the different companies, when they are compared with the total outages due to line troubles (per 100 miles of line) on line 1 of table I and expressed on a per cent basis of the total line faults, the results are alarmingly consistent for some of the companies. For example, comparing line 1 of table I with line 1 of table II, it is seen that of the total line faults, the following percentages are permanent for the various companies: 64 per cent, 61 per cent, 6 per cent, 65 per cent, 70 per cent, 7.5 per cent, 85 per cent, and 5.7 per cent.

It appears from these figures that 5 of the 9 companies have percentages of permanent line faults varying from 64 to 85 per cent, 3 companies from 5.7 to 7.5 per cent, and in the case of the ninth company there seems to be more permanent faults than total faults on the circuits.

It would be very interesting to know more about the differences in conditions existing between 5 companies with high percentages of permanent faults and the 3 companies with low percentages. A great number of conditions might be responsible, such as nature of area served, type of construction, tree conditions, relay protection, etc. The differences are so great, however, that there should be some apparent reason for them.

The idea of instantaneous tripout on initial fault and time delay on reclosure is especially attractive from the standpoint of preventing permanent damage. It would be interesting to know from those companies using it, whether it has had any influence in this respect.

L. M. Olmsted (Duquesne Light Company, Pittsburgh, Pa.): Mr. Lincks and Mr. Benner have presented a very good account of the technique of co-ordinating overcurrent protection on a distribution system.

Similar studies by the Duquesne Light Company have indicated several difficulties, however, which might well be considered at this time.

The diagram below shows curves for a 10-kva 2,400-volt transformer serving an individual consumer. Full-load current on the secondary is 42 amperes, and inasmuch as it is common practice to permit loading up to 150 per cent of rating, this current may be as great as 63 amperes. The next larger commercial size of fuse is 100 amperes which size is taken as the basis of co-ordination. The secondary connections are 3-wire grounded-neutral and practically all of the consumers' load is connected line-to-neutral, consequently short circuits are practically all from one line to netural. This gives a transformation ratio of 2,300 to 115, so that 20 amperes primary current is equivalent to 400 amperes of secondary short-circuit current. Curves for 3 different types of 100 ampere secondary fuses are shown on this basis.

There seems to be a growing trend toward thermally tripped circuit breakers, however, and it is advisable to compare their characteristics with the curves of the fuses which they replace. The commercial size next larger than the 63 amperes load current for this 10-kva transformer is 70 amperes; corresponding curves are shown on the diagram. It is very evident that these devices are much slower blowing than fuses, which has permitted the sales feature of being less subject to tripping by motor-starting currents. The co-ordination of primary fuses, however, must be with the circuit breaker rather than fuses.

In order to provide some degree of protection to the transformer and secondary system, it is desirable to use a primary fuse of about 15 amperes continuous rating. The curves for four such fuses, each one rated for 100 per cent current and 3 of them universal, are shown as *A*-15, *B*-15, *C*-15, and *D*-15. *A*-15 co-ordinates with ample margin but has a rather high continuous carrying capacity. *B*-15 is very close at heavy currents but probably co-ordinates satisfactorily and has a more reasonable continuous-carrying capacity. *C*-15 and *D*-15 fail to co-ordinate for short circuits exceeding approximately 6 times full-load current. This comparison demonstrates the marked difference in characteristics for supposedly interchangeable fuses of different manufacture.

The comparatively recent agreement among fuse manufacturers to rate fuses for continuous operation at 100 per cent current might seem to offer some hope that the characteristics of fuses gradually will be brought into closer agreement. In that light it is unfortunate that manufacturers *B* and *C* both superseded a fuse with characteristics which would have co-ordinated

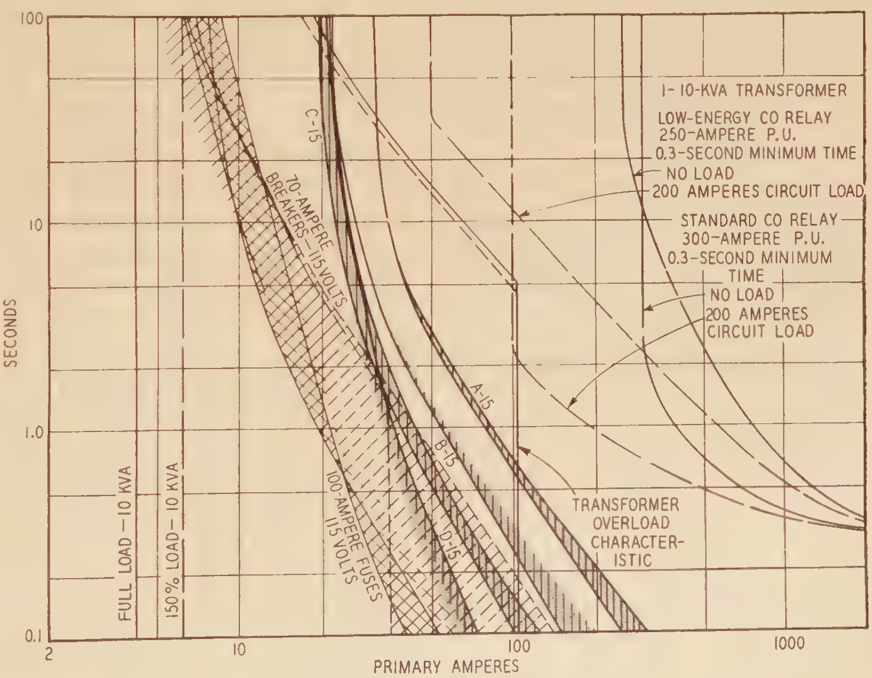


Figure 1

more satisfactorily when they introduced *B*-15 and *C*-15. There seems to be a decided trend toward "fast blowing" primary fuses, probably intended to afford better selective action between transformer fuses and line sectionalizing fuses. This trend is entirely opposite to the trend of consumers' overload protection and seriously complicates the co-ordination of primary and secondary protective devices.

G. F. Lincks and **P. E. Benner:** The authors greatly appreciate the contributions made by those discussing this paper. This should enhance its value for those interested in the improvement of service continuity on distribution systems.

It is assumed that the 100-ampere fuse and 70-ampere circuit breakers referred to by Mr. L. M. Olmsted, are those located at the meter board on the consumer's premises.

The design of the fuse links referred to as "*C*15" in Mr. Olmsted's discussion, was made to fit a scientifically developed set of time-current curves as shown in figure 4 of the published paper. In developing these, each fuse link was made to blow within 5 minutes at as low a percentage above the rating as possible and still carry the rating continuously and without exceeding a temperature rise of 30 degrees centigrade above an ambient temperature of 40 degrees centigrade. Motor starting acceleration time-current curves were plotted for motors representing 75 per cent of full-load current of a transformer fused with a fuse link rated at 2 times the full-load current, which is the lowest of the fusing practices developed and quite generally used by the utilities for the primary of distribution transformers. These practices apply to fuse links rated to blow at 150 per cent of their ratings within 5 minutes and a similar application was made in the development of the curves in figure 4

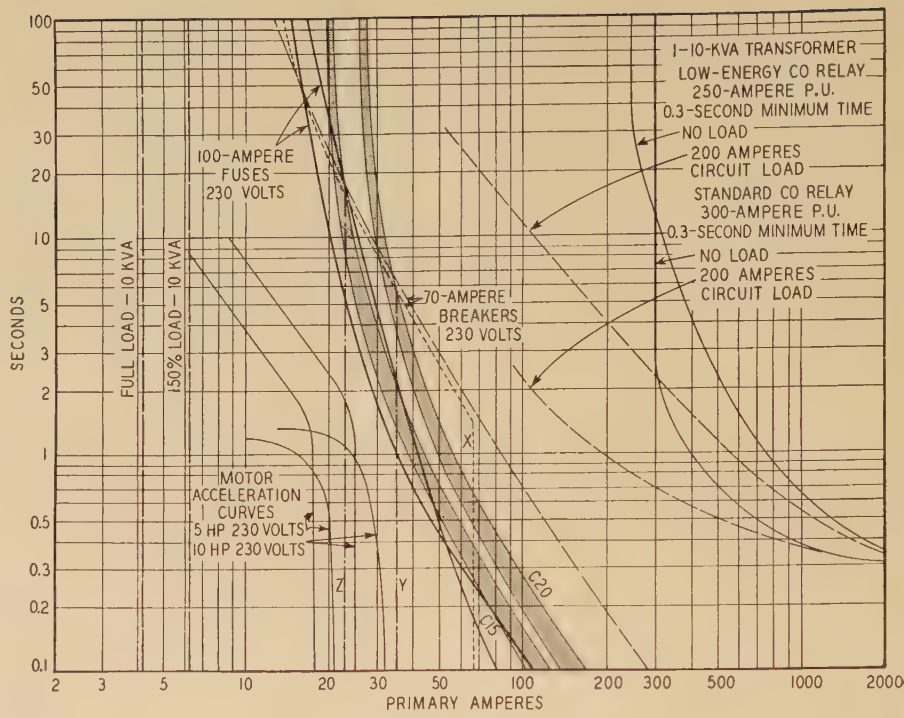


Figure 3. Mr. Olmsted's curves replotted for 230-volt fault conditions and with 5- and 10-horsepower 230-volt motor acceleration curves

of the published paper, although some fuse links were renamed later in order to meet the new 100 per cent continuous current carrying rating standards. Induction type relay curves approach these motor starting current curves in the range between one and 3 seconds, thus quite definitely locating the one-to-3-second range of the time-current curves for the fuse links best adapted to co-ordinate with both. The shorter-time, higher-current range of the fuse-link curves was made to co-ordinate with plunger-type relays of which there are many in service and with the interrupting rating of the fuse cutout for which the fuse links are designed. The curves for all ratings were made to parallel each other as closely as possible so the smaller fuse links will protect the larger fuse links to the highest currents possible when connected in series for line sectionalizing. The design of the actual fuse links was made so as to produce these scientifically developed curves.

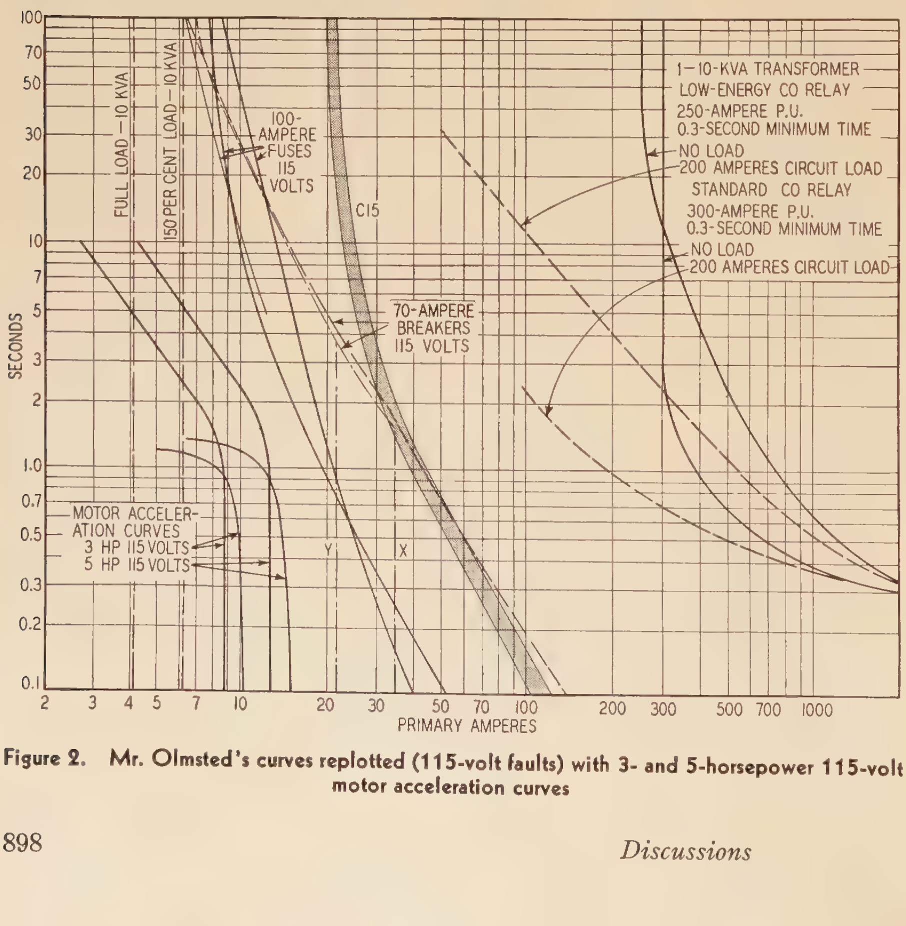


Figure 2. Mr. Olmsted's curves replotted (115-volt faults) with 3- and 5-horsepower 115-volt motor acceleration curves

In figure 2, the full-load full-voltage motor-starting-acceleration time-current curves for 3- and 5-horsepower 115-volt motors are plotted with a duplicate of Mr. Olmsted's curves for the 100-ampere fuses, the 70-ampere circuit breakers and the "*C*15" 15-ampere fuses. The 3-horsepower motor has a full-load current of 28 amperes or 65 per cent of the full-load current of the 10-kva transformer, thus closely approximating that used in the development of the "*C*15" curves. The full-load current of the 5-horsepower motor and 10-kva transformer are approximately equal. It can be seen that both of these motor-starting curves indicate successful co-ordination with the 100-ampere fuse, while the less inverse curves of the circuit breakers allow an excessively wide range above the motor-starting curves. As a result, these slower—less inverse—characteristics of the breaker prevent reasonably close co-ordination with branch-line plug or cartridge fuses (connected on either the line or load side) on the consumer's premises and, as Mr. Olmsted points out, interfere with the application of the primary fuse links scientifically developed to provide close co-ordination with both induction relays and motor-starting currents. Actual studies by the engineers of several utility companies have shown that slower (less inverse) primary fuse link characteristics than the "*C*15" curves will necessitate higher feeder circuit breaker relay settings, which

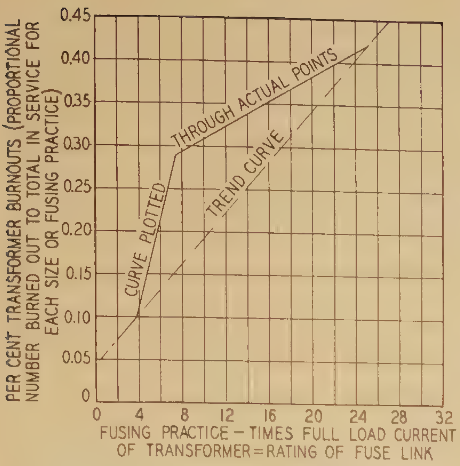


Figure 4. Primary fusing practice—transformer burnout curve

Based on using an 8-ampere fuse link with 1 1/2-, 5-, 10-, and 15-kva 4,800-volt transformers which Mr. Seelye states is the practice for the transformers to which the data in his discussion applies

Transformer Rating	Fusing Practice × Full Load	Per Cent Burnouts Per Size Installed
1 1/2	25.0	0.42
5	7.2	0.29
10	3.8	0.10
15	2.5	0.08

in turn will interfere with the protection on the transmission system. This indicates the need for making the time-current characteristics of the secondary circuit breakers more inverse.

Mr. Olmsted has chosen the less conservative example on the basis that the majority of faults will occur between line and neutral (115 volts) where the transformation ratio for short circuit and surge currents is 20 to 1. Figure 3 illustrates the effect of line-to-line 230-volt faults for the same installation except with 5-horsepower and 10-horsepower, 230-volt motors having full-load currents of 23 and 43 amperes, respectively. It can be seen that a 20-ampere primary fuse link "*C*20" figure 3 is necessary instead of the 15-ampere fuse link "*C*15" in order to be protected by the 100-ampere cartridge fuse. However, this is not unreasonable when one considers that with the wide variation in the many different makes of cartridge fuses purchased on the open market out of the control of the utility engineer, the 100-ampere rating, in meeting the Fire Underwriters' specifications, blows at 150 amperes secondary current or 15 amperes primary current (150 per cent of its rating) within 4 minutes, while most 15-ampere primary fuse links blow at 22.5 amperes primary current (150 per cent of its rating) within 5 minutes. The curves in figure 3 show the conditions of figure 2 made worse by the lower transformation ratio, thus accentuating the need for speeding up (making more inverse) the characteristics of secondary circuit breakers for use on the consumers' premises, in order that as a comparatively new device entering the field, it may better line up with existing conditions and equipment.

The instantaneous trip shown by Mr. Olmsted for one of the 70-ampere circuit breakers, see curve *X* figures 2 and 3, as taken from Mr. Olmsted's curves, might be helpful on 115-volt faults if set to cut off at lower currents, see curve *Y* figure 2. However, as shown by curve *Y* figure 3, this does not appear to offer a solution on 230-volt faults, where the full-load current of the 230-volt motors closely approximates the full-load current of the transformer. With smaller 230-volt motors having full-load currents approximately 75 per cent of that for the transformer or even large 115-volt motors, the setting of the instantaneous trip might be made low enough, curve *Z* figure 3, to permit co-ordination with the motor acceleration curves and the "*C*20" primary fuse links of figure 3 but the co-ordination of branch line, plug, or cartridge fuses might prove difficult with such an installation.

With this background and to more directly answer Mr. Olmsted's question, the trend has been to faster time-current characteristics for primary fuse links during the past years,[1,2] so as to permit the closer co-ordination with existing induction type relays which many utility engineers have declared a vital necessity.

Mr. H. D. Seelye has made a real contribution in enlarging on the economies of secondary protection for individual transformers and outlining the advantages of the secondary banking, which he calls "solid," meaning with fuses in the secondary leads and not everything solidly tied together as is being used by another utility pioneering in this phase of secondary protection.[3] Mr. Seelye's data confirms that given in table I and II of the paper in showing that the normal primary fusing practices just mentioned are affording a high degree of protection to the transformer except for the lower kva ratings where the ratio of fuse rating to transformer full load current is much higher. The curve figure 4 shows how the percentage of transformer burnouts per size installed, as taken from the tabulation in Mr. Seelye's discussion, varies with the fusing practice. It is of interest to note that 3 of the points fall on a straight curve, indicating a trend which, of course, may or may not apply to higher-rated transformers. Mr. Seelye's records of the types of loading and any other causes for the higher percentages of burnouts with 5-kva transformers would be of value. Possibly, the increased use of 5-kva transformers for range and hot-water heating loads might be an explanation for the higher percentage of burnouts which, if true, would also raise the percentage of burnouts for 3-kva transformers above such a trend curve plotted for other utilities' systems where they are using these for similar loads. As Mr. Seelye indicates, the use of secondary protection depends on the degree of improvement in protection which can be secured and a comparison of the savings made possible thereby *vs.* the cost of securing these savings for the particular conditions pertaining on each specific system.

It was not the intent of the authors to favor the "sectionalized" or "loose" banking or any of the other types of protection covered in the published paper, but rather to investigate the effect of each of the trends in distribution protection so utility engineers may be better enabled to decide which best suits his requirements. If emphasis was placed on the "sectionalized" banking, it was because this method appears to predominate in the installations known to the authors and because it does permit securing the benefits without increasing the primary fusing practice. Actual service experience has proved that this latter is important for those wishing to sectionalize the lines now or in the future. Mr. Seelye points out that the so-called "solid" banking is best adapted to ring feeders where the secondaries of a large number of transformers are connected together which he states is not always practical to adapt to existing systems. He rates the "solid" and "sectionalized" or "loose" banking as equal where 2, 3, or 4 transformers are connected together, although having previously discounted the effect of each on line sectionalizing as discussed in the paper since he believes this is not a serious operating problem.

Mr. E. J. Burnham's discussion of the experiences of the New York Power and Light Corporation with fused line sectionalizing, which includes not only straight radial circuits but those that are more complicated and interconnected, exemplifies the growing trend toward this effective method of reducing consumer minutes outage. The improvements embodied in modern fuse cutouts and fuse links[1,2] along with the protective characteristic charts,[4] the total clearing time-current curves and the simplified methods of calculating the currents in primary line short circuits[5] now available have made primary-line sectionalizing with fuses practical even to a much greater degree than heretofore. Mr. Burnham supports the paper in stating that more actual operating data expressed in numerical terms are necessary to help toward the more effective application of this and other methods of distribution protection. However, as exemplified in Mr. Burnham's discussion, the practical and more general knowledge of utility engineers on the reductions in line outages by line sectionalizing when applied according to modern methods has placed this method of line protection beyond the experimental stage. In addition to the benefits mentioned by Mr. Burnham and in the paper, fused seetionalizing when applied in accordance with figure 12 of the published paper can be made effective in extending protection to the lines out beyond the point where the line impedance limits fault currents to values below the minimum pickup current setting of the feeder circuit breaker relay. Permanent faults might otherwise anneal the copper or actually burn down the lines.

Mr. G. B. Dodds has brought out an important point in regard to permanent *vs.* temporary faults. He appears to favor a system on which temporary faults predominate, whereas some other utility engineers have expressed their belief that the causes of temporary faults are subject to correction and thus believe permanent faults should predominate. Possibly this variance in viewpoint may influence the system design, which, along with the other conditions Mr. Dodds suggests, might be responsible for the difference between the 5 companies having a percentage of permanent faults varying from 64 per cent to 85 per cent and the 3 companies varying from 5.7 per cent to 7.5 per cent.

The authors appreciate Mr. Dodds calling attention to the misplaced decimal point in table II. In checking this table, other similar errors suggest reprinting the data in correct form.

Mr. Dodds expressed interest in the idea of instantaneous tripout on initial opening

Table II. Comparison of Permanent Primary Line Outages with Distribution Transformer and Secondary Outages (Reprinted to Include Corrections)

Company	1	2	3	4	5	6	7	8	9
1....Permanent line outages (per 100 miles of lines)	18.65	8.3	2.54	35.0	14.0	1.0	34.0	1.7	0.4
2....Distribution transformer and secondary outages (per 100 distribution transformers)	7.2	4.1	8.7	5.6	8.1	0.9	7.8	3.0	11.6
3....Transformers per mile	11.9	9.5	13.5		10.7		7.9		8.9
4....Transformer outages for one mile of line due to permanent line faults	2.22	0.79	3.43		1.5		2.68		0.36
5....Transformer outages for a one-mile line due to transformer and secondary faults	0.86	0.39	1.73		0.87		0.63		1.03
6....Transformer outages for a 1/2-mile line due to permanent line faults	0.505	0.20	0.83		0.38		0.67		0.09
7....Transformer outages for a 1/2-mile line due to transformer and secondary faults	0.43	0.20	0.86		0.44		0.31		0.52

of the feeder circuit breaker and time delay on reclosure so as to permit branch line fuses to isolate permanent faults. The Toledo Edison Company have reported very favorably on their experiences which we believe extend over a period of several years. One or 2 other companies in that district have also adopted this scheme. Without doubt many engineers would welcome the publishing of any operating data they have accumulated.

Mr. R. H. Earle brings out an interesting trend in rural distribution with respect to a practice of wiring residences with 60-ampere meter switches and receptacles for future needs while installing low kva transformers rated for the present load. He states that the internal transformer fuses are selected to blow on short circuits between the service wires leading to the house. However, from the available published data, internal transformer fuses in the primary leads are usually rated too high to blow even on secondary line faults close to the transformer. Thus a secondary protective device is required if faults are to be cleared between the service entrance fuse and the transformer. As shown by curves I' and I'', figure 9 of the paper, the rating of the internal transformer fuses is generally so high that there is very little, if any, range for sectionalizing the primary line even at one point. Thus the breaking up of the line into many sections even with the overlapping of fuse blowing as suggested by Mr. Earle, if possible at all, could only be accomplished by an extremely high setting of the feeder circuit breaker relay. On the other hand, the spillover gaps used for lightning protection require the positioning of the time-current characteristic curve for the relay, recloser or sectionalizing fuse, so it always functions on the lowest dynamic follow current at the gap furthest out on the line with sufficient speed to protect the gap. In many instances, this time-current characteristic curve is to the left of (faster than) the curve for the internal primary fuses in the transformer so the relay, recloser, or fuse on the primary lines operates ahead of the internal fuses. Under such conditions, all permanent transformer and line faults interrupt service on the entire feeder or the sectionalized portion. As explained in the paper some utilities, using the recloser for such service, shunt it manually with a fused cutout and fuse link rated high enough to permit the internal fuses to blow first when checking to determine whether the fault that caused the recloser to lockout is on the line or in a transformer. Counters on such reclosers have indicated as high as 25 or more operations without lock-out in one lightning storm, evidently due to gap flashovers. Such operation would make impractical two or three reclosures on repeating fuses. The experiences of any utilities employing such fuses on this type of rural circuit would be valuable.

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Pole Flexibility as a Factor in Line Design

Discussion and authors' closure of a paper by Howard P. Seelye and Myron Zucker published in the January 1937 issue, pages 91–100, and presented for oral discussion at the power distribution session of the winter convention, New York, N. Y., January 26, 1937.

F. W. Deck (Philadelphia Electric Company, Philadelphia, Pa.): This paper is a distinct contribution to the advancement of our theoretical knowledge in a field where practice has heretofore been based almost entirely upon experience and established precedent. It will be very helpful to those engineers whose problems permit the use of this theoretical knowledge of pole flexibility, to have available a theoretical basis upon which they can establish well-defined rules for the use of the men in the field. In some localities it may not be possible, due to the particular conditions involved, to utilize these theories, or it may not be necessary since their utilization is not demanded by the conditions encountered.

Within the Philadelphia Electric Company area, our engineering and operating forces have not so far encountered the need for a concentrated study of methods such as Messrs. Seelye and Zucker have developed, due to the fact that there has been a lack of the particular problem which the authors describe as existent in the Detroit district. In the development of standards for pole line construction, we have utilized the higher stress values which have been developed in the regulations and codes within recent years, and these values are leading to the use of smaller poles. It has not been necessary to make frequent use of the smaller size poles of other utilities as guy stubs.

Sometimes we "rake" the end poles of a line to a specified amount so that when the wire loads reach the normal tension at 60 degrees Fahrenheit the pole tops are in a vertical position. Of course, when heavy ice loads are applied, there is an additional deflection of the pole; but the pole, even designed thus as a semirigid structure, is not called upon to withstand a greater load than 60 per cent of the ultimate strength of the wire.

If the fixity of the pole in the ground can be precisely determined, and if no loads occur during either the period of construction or actual service which would cause a stretching of the wire to a point outside of the range covered by the initial modulus of elasticity, then the method of design prescribed in the paper can be used with accuracy. These factors, however, deserve attention and must be thoroughly taken into consideration in the application of the method described by the authors. If the pole in question is blocked against foundation movement, the likelihood of any considerable variation in its position at the base, from the fixed vertical, is very slight. However, it may not always be possible to block or concrete the base of these poles, and in such cases it is well to remember that the change of position of the top of the pole due to movement of the pole in the ground may lead to as great or even greater change in the span length, with the accompanying tensional changes in the wires than the actual flexing of the pole itself. Even if the pole is blocked below the ground line, freezing and thawing of the soil at the ground line is responsible for a difference in the resistance to movement of the base of the pole.

Also, if for some reason or other the wire is stretched during the construction to a point greater than the average tension sustained under normal conditions, the computation may be considerably in error unless some allowance for this change has been made in the selection of the wire modulus used. Heavy loading would also cause a plastic extension of the wire material and have something of the same effect. These wire effects are, however, much less pronounced in copper than in aluminum or in composite cables where aluminum is present.

A pole system is not necessarily constructed with such refinements that the effects of unequal construction loads can be entirely eliminated, and therefore it is possible that flexibility in the poles might be an

important contributing factor in this type of design, extending farther back into the line than the 2 poles of the span considered.

Wood as a material cannot be subjected to the ordinary principles of design with the same freedom as materials such as steel and concrete. The fibrous composition of wood raises shear to a much greater importance than in materials having a more crystalline and homogeneous construction. Longitudinal shear or shear parallel with the fiber, together with effect of defects in the wood on the distribution of shear are of the utmost importance in some types of wood design; and while they do not achieve nearly the importance in the cantilever pole used to support wires as they do in the horizontal beam, still they are factors not to be lightly dismissed. Their effect upon the section modulus to be used and consequently upon the proper cross section of the pole is worth while considering. Poles may when newly erected, and more frequently after they have been in service for some time, have a central section which is not of full value. The unit stresses allowed take care of these considerations to some extent, but not entirely so. The articles written by Mr. J. A. Newlin, of the Forest Products Laboratory, United States Department of Agriculture, are interesting in regard to these last points since they are the result of Mr. Newlin's long and varied experience in testing, designing, and using wood in all kinds of work.

With regard to the methods which are developed in the paper in determining the bending in the pole and the final position of equilibrium, it is well to remember that in cases where lateral as well as transverse loads come upon the same pole, sometimes at different levels, the "deflection constant p" is affected and should be either a partial constant for each direction of bending or else a combination constant for the resultant direction of bending. If these loads are applied at different levels, the determination of the combined bending effect is somewhat more involved, but some answer to this question must be determined, or else only a part of the stress in the pole will have been considered and hence the computations may be in error.

This paper should arouse great interest among those who have to do with the design and construction of wood-pole lines, and should encourage studies and experiments to determine the movement of a pole in the ground when the pole is not blocked, and where average types of soil are encountered. Further studies should also be developed to show the combined effects of vertical and horizontal longitudinal and transverse loads occurring simultaneously. Also, in this connection it would be interesting to know the magnitude of the actual guying effect which the supported wires provide against lateral transverse deflection in the individual poles in a long line of poles.

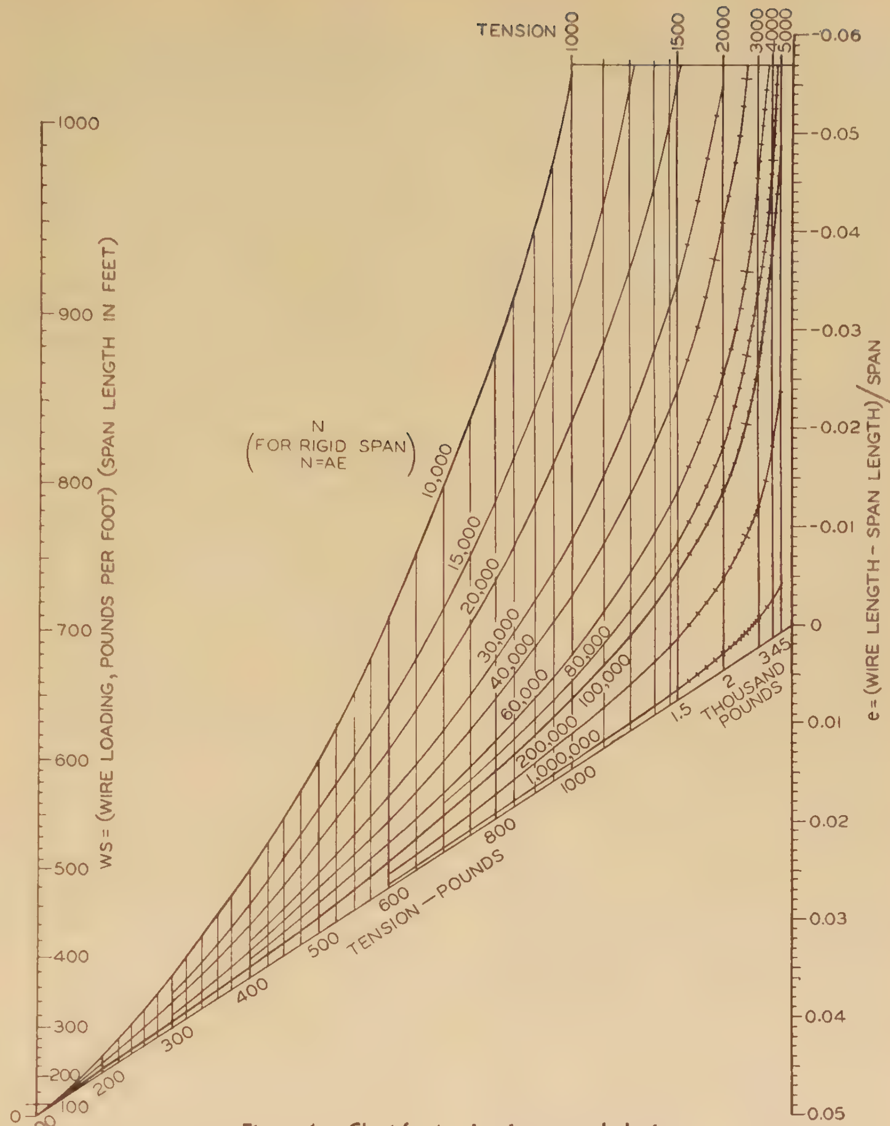


Figure 1. Chart for tension in suspended wires

A. B. Campbell (Edison Electric Institute, New York, N. Y.): The presentation of this paper offers a needed opportunity to discuss wood-pole flexibility in connection with the design of overhead lines. Since the second edition of the National Electrical Safety Code was published about 20 years ago, it has contained a general requirement that did not permit taking into account the deformation or deflexion of any part of a supporting structure in the calculation of stresses. This requirement has been included in subsequent editions. Inasmuch as this code forms the basis for the minimum construction requirements in force by several state regulatory commissions, the requirement just mentioned is given legal status where this part of the code has been adopted.

Actually, flexibility is oftentimes desirable in the supporting structure of an overhead line, particularly when these supports are wood poles. It constitutes one of the greatest assets of a structure in resisting ice and wind loads, and probably is the explanation why many lines have not failed when theoretically they might have been expected to do so.

The code requirement referred to above has made it necessary to assume a wood pole as a rigid structure. Compliance with this assumption has usually been obtained by the use of guys or braces, some of which have in themselves introduced electrical conditions that have resulted in conductor failures which the installation of the guys were intended to prevent. Furthermore an attempt to make a wood pole into a rigid structure by the use of guys which are not required to support a constantly unbalanced load, is likely to introduce a mechanical condition which prevents the distribution and equalization of stresses throughout the pole and thus causes failure at or near the point where stresses are concentrated. There is little doubt but that a rigidly guyed pole is less capable of withstanding impact loads than one which is free to deflect within reasonable limits under load and then return to its normal position when the load is removed.

This is one phase of the problem. Another is that no generally accepted method has been developed which would make possible a precise solution. Attempts have been made and considerable thought given to the problem but several factors are involved which make an exact solution impossible. For example, the effect of moisture content in the pole and the varying conditions in earth settings are not only difficult to evaluate but vary from day to day. It is well known that a relatively small longitudinal movement of a pole top can result in excessive conductor tensions or greatly reduced clearances. Since this effect would vary quantitatively with weather conditions, no exact method of calculating this effect seems possible. Therefore the code rule previously

referred to was perhaps the best method known at the time the code was formulated to hold variations in sags, tensions, and clearances within desired limits.

The past several years have furnished a wide experience in the performance of wood poles under normal loading and storm conditions. In my opinion some of the conditions for which guys are used seldom occur and when they do the guyed pole, when properly selected, seems to possess the ability to equalize stresses and remain unbroken. For this reason I favor the omission of unnecessary guys and the use of an approximate method such as the authors of this paper have developed whereby a reasonable advantage may be taken of the inherent flexibility of a wood pole structure. It is to be hoped that further attention will be given to the subject covered by this paper and an effort made to co-ordinate loadings with the flexible characteristics of wood pole structures.

H. P. Seelye and **Myron Zucker:** Mr. Deck has summarized the elements that must be considered in designing flexible spans. However, it must be emphasized that while such items as load distribution up the pole, strength of pole foundations, elastic limit of the wire, and pole constants enter into the problem, they are by no means indeterminate.

In discussing these variables, the governing fact is this: a relatively great variation in deflection constant will cause but little change in the relation between stringing and loaded tensions. Therefore, pole and foundation movement per unit load need be determined only with reasonable accuracy. The 2 elements of uncertainty in pole flexure are variation of fiber stiffness, and vertical distribution of load. The former is admittedly a variable, although not to quite the extent that might be indicated by tests on small specimens. Deflection constants derived from tests on 15 full-size poles have agreed within ±25 per cent of calculated values. As to the latter, a reasonable approximation may be made, for wires in the same zone, by using the deflection constant for a load height equal to the square root of the sum of individual heights squared. For more widely separated loads or loads in different directions an analysis of deflections may be made. It is relatively complicated and requires solution by successive approximations as described in the paper for joint-use leads.

As to foundation movement, the results of several short-time and numerous long-time full-size tests have enabled us to specify foundation designs for various types of soil and ranges of load, so that poles may be held with a negligible or reasonably predictable foundation yield. Considering the relative unimportance of deflection constant, mentioned at the beginning of this paragraph, the accuracy is well within the limits assumed for standard loading conditions.

It is of course possible to stretch wires past their elastic limit. However, the tendency for this to happen is less in flexible spans than in rigid spans where the effect is generally neglected. In addition, a study of N will show that the wire stretching is generally a minor factor compared with pole bending.

Straight-grained woods are greatly to be preferred for holding dead-end loads, since their moduli are more consistent and they yield less initially and over a period of time than do knotty poles, due to the large bending effect in the latter when moderate loads straighten out the curved fibers surrounding the knots.

Informal discussion has shown that a chart in terms of tension instead of sag is needed for convenience in calculation. Substituting equation 6 in equation 5 gives the relation

$$e = \frac{w^2S^2}{24T^2} - \frac{T}{AE} \qquad (5a)$$

This may be charted as in figure 1, which is manipulated in the same manner as figure 9. Thus, with w_1S, N, and T_1 known e is found; appropriate changes are made in e for temperature variation and external forces; and then with e', N, and w_2S known, T_2 is read. The chart may be used whenever tensions are involved, and is especially valuable when tension is specified under one set of conditions and is to be found for another set. The range of figure 1 may be extended by using any desired scale multiplier on the wS, T, and N values (not affecting e).

Mr. Campbell mentions some variables—moisture content and pole setting—which are difficult to evaluate. This difficulty must be admitted, but it applies equally well (as do the points enumerated by Mr. Deck) to the design of poles for transverse loads. The uncertainty of actual loads and the judgment needed in specifying safety factors overshadow the other unknowns in both cases. At any rate, satisfactory results have been obtained with numerous special cases of flexible dead ends designed according to the principles outlined in the paper.

Mr. Campbell's comments bring out the advantage of flexibility under certain conditions and point to the fallacy of the common idea of "being on the safe side." This reinforces the thesis of the paper: that calculation of dead ends on the assumption of rigidity may actually make some elements in the line undersize. Regardless of the merits of unguyed poles, it is certain that where they *are* used, the design should be based on the fact of flexibility rather than the fiction of immobility.

A Review of Overhead Secondary Distribution

Discussion and author's closure of a paper by W. P. Holben published in the January 1937 issue, pages 114–22, and presented for oral discussion at the power distribution session of the winter convention, New York, N. Y., January 26, 1937.

Harold Cole (The Detroit Edison Company, Detroit, Mich.): Mr. Holben's paper is, I think, a valuable addition to the technical information on the matter of secondary-distribution economics. The secondary wires and their associated transformers form such a large proportion of the investment of an electrical distribution system that the importance of sound engineering in this field cannot be overemphasized. The comparison of the results of studies made on 5 large systems shows very little difference in conclusions, despite some rather wide variations of assumptions as to cost factors. The interesting thing is that the investigators agree that wire sizes from number 4 to number 2 are the most economical for the densities of load found largely in urban districts, and that through a rather large range of load densities there is not a great variation in the relative cost of the secondary distribution system, no matter whether number 4, number 3, or number 2 wire is selected, providing, of course, that the transformer size and spacing is selected to give the minimum cost of the combination of the 2. If the smaller wires are installed initially, the later cost of more frequent relocation of transformers or of secondary replacement, or both, offsets the initial saving in investment to a greater or lesser extent, depending on the rate of growth of load.

All of this would indicate that a rather wide latitude is possible in the proportioning of secondary copper and transformers without affecting greatly the over-all economy. The important thing to my mind, therefore, is that a program of development is laid out that is best suited to the conditions in the particular area under consideration and that it is carried out under intelligent supervision. Haphazard development results in costly rearrangements later on or else perpetuates uneconomical layouts made in an effort to take care of the immediate necessity at the least cost without consideration of over-all economy.

An effective way of providing for an orderly development of the distribution system is to draw up master plans which show the location of all poles, transformers, secondary and primary mains in all areas which have been subdivided into city lots. If the facilities are built as required in accordance with these plans, the cost of the initial extensions may be slightly higher than would be possible with expedients which take account only of the cost of providing service to the few scattered customers first applying, but in an area which is expected to build up solidly in a few years, the added cost of later rearrangement of facilities amply justifies the slightly higher first cost.

In my own company we have prepared such master plans, not only for undeveloped areas but for the older sections of the city where replacement of poles will be required in the future. In this way, the relocation of transformers and replacement of wires may often be carried out at time of pole replacement at a minimum of expense. The planning of these layouts is supervised by an engineer of long experience in distribution design and every effort is made to adapt the layout to the type of load which may be expected to develop in that area.

In residential areas we have adopted number 2 copper wire as standard for secondary mains and initial transformer spacings are usually 700 to 800 feet. The initial transformers may be as small as 5 kva but where development is expected to be rapid or where range load will probably develop, we will use the 10-kva size. A spacing of about 800 feet is necessary with these small transformers if noticeable voltage dips caused by starting of small household appliance motors are to be avoided. Ability to give adequate voltage for electric ranges in the early development stages also requires spacings of this order. The same secondary

wire and transformer spacing will be adequate for load densities up to about 50 kw per 1,000 feet. It is only necessary to change transformer sizes as the load requires. We feel that any possible saving in the use of wire smaller than number 2 in the early development stages would not justify the poorer quality of service which would result, especially in view of the present trend to more complete home electrification with the increased use of appliances equipped with electric motors as well as the larger heating appliances which will ultimately result in much greater load densities. On the other hand, the use of conductors larger than number 2 does not seem to be required in residential areas, even with the increased load densities to be expected, as a relocation of transformers on number 2 secondaries will permit going to much higher densities when they develop before the system becomes uneconomical.

Incidentally, the banking of transformers on a more or less continuous secondary main, such as practiced in Detroit and now being rapidly extended to other parts of our system where conditions are at all favorable, is very helpful in many ways to the economical development of the system. Steady state voltages are more easily maintained on the secondaries and voltage dips due to motor starting are much less troublesome, to say nothing of decreased outages due to transformer failures and less transformer capacity required.

I want to emphasize that the orderly development of a distribution system requires a trained personnel to supervise that development. The men who are responsible for this development should be men of engineering training, and should not be burdened with so much detailed routine work that they do not have time to adequately study the engineering problems involved in additions to or changes in the system. The use of master plans, however, will be of much aid to these men in helping them to make rapid decisions and still not overlook some important considerations which would not escape one who had sufficient time to study all of the conditions involved. The field engineer need then only concern himself with situations where new considerations develop which make it desirable or necessary to modify the original plans.

I want also to urge the importance of making studies such as those reviewed by Mr. Holben for each particular system. I do not wish to minimize the value of the presentation of such a review but there is some danger, I think, that some of the general conclusions may be misinterpreted by those who have not carefully studied all aspects of the problem. A study which takes account of all of the local field conditions and operating practices will make certain that development plans will be adopted which are best suited to the particular system.

W. P. Holben: Mr. Harold Cole, in his discussion of the paper "A Review of Overhead Secondary Distribution," has presented a number of points that are worthy of serious consideration. In fact, I am heartily in accord with these items as well as the results to be obtained by using his recommendations and will therefore repeat them in outline form.

1. Importance of sound engineering to include studies for each particular system

a. To account for all local conditions
b. To avoid misinterpretation of the general conclusions

2. Need for a program of development

a. Intelligent and experienced supervision
b. Master plans with future steps indicated
c. Procedure in new developments

The summary and conclusions, included in the paper, have stated some necessary exceptions to the principles recommended by the respective authors. There are other natural differences of opinion and local operating practices that will probably affect the application of these principles of design on various systems. Further study therefore along the following lines should provide valuable information and knowledge on the subject of overhead secondary distribution.

1. A classified list of necessary exceptions with the best engineering solution for the principal classifications
2. Flicker conditions and economical solutions.
3. Transformer loading practice and a summary of experience records especially for the higher per cent loadings
4. Banking transformers, single-phase, and 3-phase, for large appliance load to meet capacity and flicker conditions

Mr. Cole has referred to the practice of banking transformers in Detroit. He reports improved voltage conditions, decreased outages and less transformer capacity required for areas served in this manner. It is apparent therefore that such advantages warrant a thorough study of this type of a secondary system. Mr. Sweetman and Mr. Arnold have contributed the suggestion that the new development in transformer design and use of a secondary breaker for transformer protection warrants further development of secondaries with banked transformers at least on a trial basis. With a probable increase of flicker complaints as the appliance load increases, it follows that banking should be considered as a possible solution since this method cuts sudden voltage variations to approximately half of that experienced on radial secondaries under similar conditions.

Negative-Sequence Reactance of Synchronous Machines

Discussion and author's closure of a paper by W. A. Thomas published in the December 1936 issue, pages 1370–85, and presented for oral discussion at the synchronous machinery session of the winter convention, New York, N. Y., January 27, 1937.

S. B. Crary (General Electric Company, Schenectady, N. Y.): This paper presents a very complete theoretical and experimental analysis of the AIEE method of measuring the negative-phase-sequence reactance and should result in a more accurate description of the method of testing by the AIEE.

Figure 1 of this discussion presents in a little different way than in the paper, the

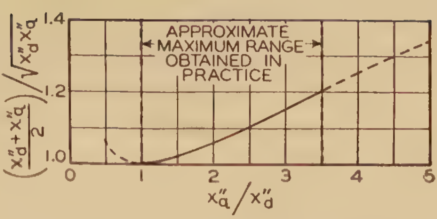


Figure 1. Ratio of the 2 expressions for x_2 as a function of the ratio of the subtransient reactances. Full line indicates approximately the maximum range obtained in practice

variation between the 2 limiting values of negative-phase-sequence reactance as a function of the ratio between x_q'' and x_d''. In this figure the approximate maximum range to be expected in practice is indicated by a solid line. As seen from this curve the maximum variation to be expected is about 20 per cent for a ratio of x_q'' to x_d'' of 3.5. This variation, of course, would decrease quite rapidly with increase in the amount of external reactance. Accordingly, the value $(x_d'' + x_q'')/2$ can be used for most practical purposes in system calculations involving this reactance.

J. C. Balsbaugh (Massachusetts Institute of Technology, Cambridge): Reference is made to the application of the negative-sequence reactance of synchronous machines to the study of power system fault currents. I should like to add several significant factors in the application of this reactance.

For a line-to-line fault in a power system as viewed from a generator, the negative-sequence reactance is given in general by the equation

$$x_2 = \sqrt{x_d'' \, x_q''}$$

in which x_2 is the equivalent negative-sequence impedance from and including the generator to the fault, x_d'' and x_q'' are the sum of the generator subtransient reactances x_{dg}'' and x_{qg}'', respectively, and the equivalent external reactance x_e. The negative sequence reactance x_{2g} of the generator, is equal to $x_2 - x_e$ and is equal to the geometric mean of the generator subtransient reactance with $x_e = 0$, and approaches the arithmetic mean of the generator subtransient reactances with x_e large relative to x_{dg}'' and x_{qg}''. The equivalent external reactance x_e is not in general the reactance from the machine to the point of fault, but in a power system with a group of machines feeding into a fault through a network, it is the equivalent reactance as viewed from the generator terminals.

It is further important that the foregoing negative-sequence reactance does not apply in general to all line-to-line faults in a power system, but only those faults that are line-to-line faults as viewed from the generator terminals. Thus consider an individual generator tied to a line through a Δ-Y grounded transformer and a ground fault on the line. In this case a line-to-ground fault on the line becomes an equivalent line-to-line fault on the generator and x_{2g} is determined as given in the foregoing, and x_e must be determined as an equivalent impedance as viewed from the generator terminals.

It can also be shown that the negative-sequence reactance in general for a line-to-

Table I. Definitions of Negative-Sequence Reactance

Method	Analytical Expressions: Fundamental	Analytical Expressions: Root-Mean-Square	Numerical Value ($x_d' = 0.35$, $x_q = 0.70$, $x_d = 1.0$): Fundamental	Numerical Value: Root-Mean-Square
(1) Application of sinusoidal negative-sequence voltage	$\frac{2x_d' x_q}{x_q + x_d'}$	$\frac{\sqrt{2}x_d' x_q}{\sqrt{x_q^2 + x_d'^2}}$	0.47	0.44
(2) Application of sinusoidal negative-sequence current	$\frac{x_q + x_d'}{2}$	$\frac{1}{2}\sqrt{(x_q + x_d')^2 + 9(x_q - x_d')^2}$	0.53	0.74
(3) Initial symmetrical component of sudden single-phase short-circuit current	$\sqrt{x_d' x_q}$	$x_d'(\sqrt{1 - b^2} - 1) + \sqrt{x_d' x_q} \times \sqrt{1 - b^2}$	0.50	0.48
(4) Sustained single-phase short-circuit current	$\sqrt{x_d' x_q}$	$x_d(\sqrt{1 - b^2} - 1) + \sqrt{x_d' x_q} \times \sqrt{1 - b^2}$	0.50	0.47
(5) Same as (4) with 0.35 p.u. external reactance		$\frac{x_q + x_d'}{2}$		0.50
(6) AIEE				0.53

ground fault (as viewed from the generator terminals) in a power system is

$$x_2 = \sqrt{\left(x_d'' + \frac{x_0}{2}\right)\left(x_q'' + \frac{x_0}{2}\right)} - \frac{x_0}{2}$$

in which x_2 is the equivalent negative-sequence reactance from and including the generator to the fault, x_d'' and x_q'' are the sum of the generator subtransient reactances x_{dg}'' and x_{qg}'', respectively, and the equivalent external reactance x_e and x_0 is the equivalent zero-sequence impedance from and including the generator to the fault and is equal to sum of the generator zero-sequence impedance x_{0g} plus the equivalent zero-sequence external impedance x_{E0} to the fault. The negative-sequence reactance of the generator x_{2g} for the condition is equal to $x_2 - x_e$.

Thus it is seen that accurate determinations of negative-sequence impedances of generators for use in connection with fault studies in power systems involves the circuit connections and other system impedances. These and other considerations should be taken into account in the measurement of negative-sequence impedances of synchronous machines and in their application.

C. F. Wagner (Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): Mr. Thomas is to be congratulated in raising the general question of the nature of the negative-sequence reactance of synchronous machines. A particularly valuable contribution is his analytical proof that the AIEE method of measuring the negative-sequence reactance gives a quantity equal to the arithmetic mean of the reactances in the 2 axes.

In reading this paper I have been prompted to make a table to show some of the methods that might be suggested to measure the negative-sequence reactance. In preparing this table a salient-pole machine without amortisseurs has been considered because the effects in question should be pronounced in such a machine. Resistances will be neglected. The first method consists in applying a sinusoidal set of negative-sequence voltages to the machine. Using the fundamental component of current in defining the reactance results in the expression[5]

$$\frac{2x_d' x_q}{x_q + x_d}$$

but if x_2 be defined in terms of the root-mean-square values the reactance is equal to

$$\frac{\sqrt{2}\, x_d' x_q}{\sqrt{x_q^2 + x_d'^2}}$$

However, if a sinusoidal set of negative-sequence currents be made to flow through the machine a fundamental and third harmonic voltage are set up across the armature. In terms of the fundamental component x_2[5] is equal to $x_q + x_d'/2$ and in terms of the root-mean-square values is equal to

$$\frac{1}{2}\sqrt{(x_q + x_d')^2 + 9(x_q - x_d')^2}$$

If x_2 be defined as such a quantity which with x_d' will give, upon applying symmetrical components, the proper fundamental component of current for the initial a-c component of a suddenly applied single-phase short-circuit current, then x_2 is

$$\sqrt{x_d' x_q}$$

and to give the proper root-mean-square value of current x_2 is

$$x_d'(\sqrt{1 - b^2} - 1) + \sqrt{x_d' x_q}\ \sqrt{1 - b^2}$$

This is the method described in paragraph 184 of the Preliminary Report on a Proposed Test Code for Synchronous Machines (January 1937).

If x_2 be defined as that quantity which will give the proper fundamental component of sustained single-phase short-circuit current when the method of symmetrical components is used, then x_2 is again

$$\sqrt{x_d' x_q}$$

and to give the proper root-mean-square value of current, x_2 should be

$$x_d(\sqrt{1 - b^2} - 1) + \sqrt{x_d' x_q}\ \sqrt{1 - b^2}$$

The AIEE method which is also based upon the sustained single-phase short-circuit test but with different metering connections gives, as Mr. Thomas has shown, the value of x_2 as $(x_q + x_d')/2$.

It is difficult to draw conclusions of the relative merits of the different expressions until numerical values are inserted. To this end a typical machine was chosen having the constants

$$x_d' = 0.35$$
$$x_q = 0.70$$
$$x_d = 1.0$$

and the numerical values corresponding to the different analytical expressions were tabulated on the right-hand side of the table.

Let us now analyze these results in view of the utility of the quantity and the applicability of the method as a testing means. The greatest use of x_2 is in connection with short-circuit and stability studies. It would appear then that the results obtained by the root-mean-square values for the single-phase short-circuit tests, would be the most important, preference being given to the sustained value because it results in a somewhat smaller value of reactance and also, because it does not require an oscillograph, is an easier method to apply. The AIEE method gives a value of x_2 somewhat greater than the value obtained by the single-phase short-circuit test. With regard to the ease in making the test it will be noted that the only difference between the single-phase short-circuit method and the AIEE method is that the latter requires an extra wattmeter whereas the former requires a previous knowledge of the synchronous reactance. The difficulty of obtaining either a sinusoidal negative-sequence voltage or current would eliminate the first 2 methods as test methods.

I am therefore submitting this discussion for your consideration. It would appear that the sustained single-phase short-circuit test for root-mean-square values is a better test for salient-pole machines than the present AIEE method. In terms of the test values this quantity is expressed by the equation

$$x_2 = \frac{\sqrt{3}\, E}{I} - x_d$$

where

I = root-mean-square value of armature current in the short-circuited phase

E = open-circuit voltage before the short circuit is applied or the no-load voltage corresponding to the field current at which I is read

For turbogenerators saturation introduces variables of such greater magnitude that the appropriate method of measuring the unsaturated value becomes inconsequential. Perhaps the best solution for turbogenerators is to simply use the subtransient reactance.

W. A. Thomas: I wish to emphasize the need of agreement on the use or abandonment of the per-unit system of notation. I have deliberately avoided throughout my paper such short-hand systems as per-unit or per-cent notation.

To a large group of engineers and especially to students who are reading the literature for applications of fundamental principles, such special systems are not easily understood. Some equations when written in a per-unit system lose their dimensional check and thus invite confusion.

May I suggest a return, in all synchronous-machine papers, to the use of fundamental units of voltage, current, and reactance?

Two-Reaction Theory of Synchronous Machines

Discussion and author's closure of a paper by S. B. Crary published in the January 1937 issue, pages 27–31, and presented for oral discussion at the synchronous machinery session of the winter convention, New York, N. Y., January 27, 1937.

W. V. Lyon (Massachusetts Institute of Technology, Cambridge): Mr. Crary's method of analysis is particularly suited to transient conditions of operation. For some cases of steady-state operation a simpler method of analysis may be preferred. The criterion for self-excitation of a salient-pole machine when it is running synchronously ($s = 0$) with the field circuit open and delivering current to a balanced capacitive load having series constants of R and X was given in my discussion of "Synchronous Machines—I," by Doherty and Nickle, AIEE, page 947, 1926). In this discussion I said:

"There is a problem of some interest that the authors did not mention. It is that of a synchronous generator which, when feeding an open-circuited transmission line, loses its field excitation. If R and X represent the equivalent resistance and reactance of such a line on open circuit then it is readily shown for this case that

$$(R + r)^2 = -(X + x_q)(X + x_d) \tag{1}$$

This shows that X is capacitive and lies between x_q and x_d. Since the values of x_q and x_d depend upon the saturation, a graphical solution of the foregoing relation can be made which will determine the saturation, and from that the terminal voltage can be found."

This equation 1 is derived from the equations which apply to the steady-state operation of a salient-pole synchronous machine.

$$\left.\begin{aligned} E &= (R + r)I_q - (X + x_d)I_d \\ 0 &= (R + r)I_d + (X + x_q)I_q \end{aligned}\right\} \tag{2}$$

where E is the excitation electromotive force due to the d-c field and R and X are the series resistance and reactance of the capacitive load (X is inherently negative).

If $E = 0$ it follows that

$$(R + r)^2 = -(X + x_q)(X + x_d)$$

from which the critical value of X for self-excitation is

$$X = \frac{-(x_d + x_q) \pm \sqrt{(x_d - x_q)^2 - 4(R + r)^2}}{2}$$

This agrees with Mr. Crary's equation 24. The greatest value of X for which self-excitation can occur is determined by substituting for x_d and x_q their *unsaturated* values. If it be assumed that there is *no* resistance in the circuit, either $(X + x_d)$ or $(X + x_q)$ equals zero. Due to the effect of the reluctance toque, the machine will undoubtedly operate stably so that $I_q = 0$ and hence it is $(X + x_d)$ that equals zero. The synchronous reactance in the direct axis equals $x_m/k + x_a$, where x_m is the unsaturated value of the magnetizing reactance in the direct axis and k is the saturation factor (see "Saturated Synchronous Reactance," C. Kingsley, Jr., AIEE, March 1935). Consequently

$$|X| = \frac{x_m}{k} + x_a$$

or

$$k = \frac{x_m}{|X| - x_a} \tag{3}$$

Since x_m and x_a are both constant, the value of the saturation factor for any value of X numerically less than $(x_m + x_a)$ but numerically greater than x_a can be found, and hence the electromotive force E_a due to the resultant air-gap flux can be determined. The terminal potential V is

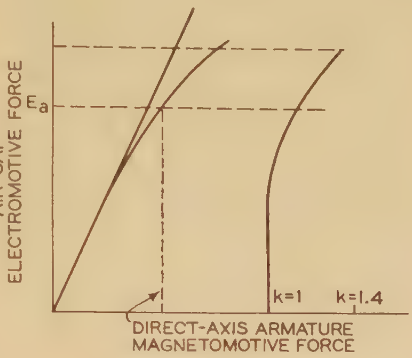


Figure 1

$$V = \frac{|X|}{|X| - x_a} E_a \tag{4}$$

The resistance $(R + r)$ can be taken into account if desired, but the expressions are not as simple. In this case the stable operating point depends both upon the direct-axis synchronous reactance and upon the quadrature-axis synchronous reactance. It is necessary to assume in what manner *each* of these reactances is affected by saturation. As a first approximation assume that the magnetizing reactances in each axis are affected *equally* by saturation. That is, assume that

$$x_d = \frac{x_{md}}{k} + x_a \tag{5}$$

$$x_q = \frac{x_{mq}}{k} + x_a \tag{6}$$

This approximation is better when the resistance, $(R + r)$, in the circuit is well below its limiting value of $\frac{x_d - x_q}{2}$ for which condition the internal power-factor angle is 45 degrees and I_d equals I_q. If these values of x_d and x_q are substituted in equation 1,

$$\frac{1}{k} = \frac{-(X + x_a)(x_{md} + x_{mq})}{2x_{md}\,x_{mq}} \pm \frac{\sqrt{(X + x_a)^2(x_{md} - x_{mq})^2 - 4x_{md}\,x_{mq}(R + r)^2}}{2x_{md}\,x_{mq}} \tag{7}$$

It follows that the greatest numerical value of

$$\frac{R + r}{X + x_a}$$

is

$$\frac{x_{md} - x_{mq}}{2\sqrt{x_{md}x_{mq}}}$$

This determines the greatest value of the power factor at the air gap in terms of the unsaturated values of the magnetizing reactances in the 2 axes. The sign before the radical in equation 7 must be taken so that k is greater than one. If both values of k are greater than one, the larger value should be chosen, since the flux will stabilize itself nearer the direct axis than the quadrature axis.

Consider the following numerical case: Let

$x_{md} = 0.85$ $\quad$ $X = -0.80$
$x_{mq} = 0.40$ $\quad$ $R + r = 0.20$
$x_a = 0.15$

Whence, using the minus sign before the radical, $k = 1.07$. If the plus sign is used before the radical, $k = 0.764$. The greatest value of $(R + r)/(X + x_a)$ is 0.386.

From equation 2, since $E = 0$,

$$\frac{I_q}{I_d} = \frac{R + r}{X + x_q}$$

The tangent of the angle between the axis of the field pole and the axis of the fundamental component of the armature flux is

$$\frac{I_q\,x_{mq}}{I_d\,x_{md}}$$

and in this numerical example is

$$\frac{0.20}{-0.80 + \frac{0.40}{1.07} + 0.15} \times \frac{0.40}{0.85} = 0.341$$

The displacement of the armature flux with respect to the field poles is 20 degrees. This small displacement tends to justify the assumption that saturation affects the magnetizing reactances in the two axes equally

There is another point that I wish Mr. Crary would discuss. It is well known that an induction generator may self-excite on a capacitive load. With a cylindrical rotor there is no tendency of the rotor to occupy one position rather than another with respect to the rotating armature magnetomotive force. On the other hand, there is a strong tendency for the rotor of a salient-pole machine to lock with the rotating armature magnetomotive force and run so that the quadrature component of the armature current is just sufficient to satisfy the condition that the power developed $I_d I_q (x_d - x_q)$ is sufficient to carry the load $I^2(R + r)$. What is the criterion which determines whether the machine will run as an induction or as a synchronous generator? If the resistance, $(R + r)$, in the circuit is greater than its critical value of $(x_d - x_q)/2$ so that the machine cannot operate stably as a synchronous generator, will the machine operate stably as an induction generator at a slip sufficient for the development of the necessary power?

C. Concordia (General Electric Company, Schenectady, N. Y.): We have recently had occasion to apply the methods given by Crary to the determination of the stable and unstable regions of operation of an induction motor when operating with series capacitance. Curves have been determined for induction motors similar to figure 1 of the paper. In this case only the unshaded portion of the unstable region of figure 1 appears since the ordinary induction motor has a symmetric rotor. Takahashi (reference 4 of the paper) has given similar induction motor curves for some cases and our results have been in complete agreement with his.

Also by a simple extension of the theory to the case of a resistor in shunt with the series capacitor we have shown that for this extended case, the final equations 14 and 15 of the paper will still apply if only the first p in each of these equations is replaced by

$$\left(p + \frac{x_c}{R}\right)$$

where R is the shunt resistance. The complexity of the equations is therefore not increased and the only change is in the introduction of the quanity x_c/R, which may be interpreted as the reciprocal of the time constant of the capacitor-resistor circuit considered by itself. Using these extended equations the regions of stable and unstable operation of induction motors have been determined as affected by the value of shunt resistance. It has been found that if x_c/R be plotted as a function of x_c just as the series resistance r was plotted in figure 1 of the paper, the unstable regions in the 2 cases are very similar in both form and magnitude.

S. B. Crary: Professor Lyon has made an analysis of the phenomena of self-excitation based upon the steady state equations, that is, i_d and i_q are constants for any given set of circuit conditions. The phenomena cannot be properly described by such an analysis, as self-excitation is produced under the conditions when the armature magnetomotive force is pulsating with respect to the direct and quadrature axes, i_d and i_q are varying with time. From the steady state equations for the direct and quadrature components of armature current (equations 33 and 34) one might suspect that the critical values of armature circuit capacitance (x_c) corresponds to the condition when the denominator of this expression equals zero. However, the denominator being equal to zero merely indicates that the steady state components of armature current would be very large at 2 definite values of capacitance (infinite neglecting saturation) if the field excitation or armature voltage is finite.

The condition when the denominator of the steady-state equations equals zero corresponds to the 2 points at which one of the roots of equation 21 (with $T_0 = 0$) is zero. This corresponds to the points at which the roots change sign. The time constant of build-up of the armature current is infinite. Accordingly, the transient and steady-state equations are in agreement at these 2 critical points, but the steady-state equations do not by themselves indicate the region of self-excitation.

In order to explain why self-excitation will occur for values of x_c from x_d to zero, Professor Lyon says "Due to the effect of the reluctance torque the machine will undoubtedly operate stably so that $i_q = 0$ and hence it is $(X + x_q)$ that equals zero." No reluctance torque as ordinarily defined exists unless there is an applied armature voltage. If self-excitation exists i_q will not be a constant value equal to zero, so that the explanation based upon the steady-state equations is misleading and unnecessary.

Professor Lyon asks about stability and "What is the criterion whether a machine will run as an induction or as a synchronous generator?" A machine will run as a synchronous generator when connected to an impedance load when there is a unidirectional field excitation corresponding to that produced by residual or d-c excitation. The machine will operate as an induction machine if the circuit constants and the speed are such as to produce self-excitation. Stability is determined by the balance between the electrical and mechanical torques. No electrical torque will be developed for the case when there is no field excitation or applied armature voltage unless the machine self-excites. If the machine self-excites the electrical torque after the currents have reached their maximum values as limited by saturation will pulsate if the machine is of salient pole construction, but will be constant if the rotor is symmetrical.

The results of Mr. Concordia's work, which he has only very briefly described in his discussion, constitute an important extension of the theory, as many cases occur in practice which do not correspond to the comparatively simple cases studied in this paper. It is hoped that his results will shortly be made generally available by presentation to the AIEE.

There is one point in regard to the derivation of equations 18 and 19 which it would be well to point out at this time. In the derivation of these equations for i_d and i_q, the changes in field excitation were neglected, that is, $\Delta E_{fd} = \Delta E_{fq} = 0$. This assumption was of course unnecessary and the components of i_d and i_q due to the field excitation voltages, E_{fd} and E_{fq} can be determined in a similar manner to that used for determining these components due to e_d and e_q. Since several readers of the paper have asked in regard to these components, it was deemed advisable that they be given in this closing discussion. The direct and quadrature axes components of armature current, including the components due to the field excitation are given below:

$$i_d = \frac{\begin{gathered}-\{[p^2 + (1-s)^2]Z_q(p) + px_c\}e_d - \{[p^2 + (1-s)^2](1-s)x_q(p) - (1-s)x_c\} \\ e_q\{[(1-s)^2 + p^2]^2 x_q(p) + [(1-s)^2 + p^2]pr - [(1-s)^2 - p^2]x_c\}G_d(p)E_{fd} - \\ (1-s)\{[(1-s)^2 + p^2]r + 2px_c\}G_q(p)E_{qd}\end{gathered}}{A(p)} \tag{18a}$$

$$i_q = \frac{\begin{gathered}+\{[p^2 + (1-s)^2](1-s)x_d(p) - (1-s)x_c\}e_d - \{[p^2 + (1-s)^2]Z_d(p) + px_c\}e_q + \\ (1-s)\{[(1-s)^2 + p^2]r + 2px_c\}G_d(p)E_{fd} + \\ \{[(1-s)^2 + p^2]^2 x_d(p) + [(1-s)^2 + p^2]pr - [(1-s)^2 - p^2]x_c\}G_q(p)E_{fq}\end{gathered}}{A(p)} \tag{19a}$$

It will be noted that all of the components of current have the same denominator $A(p)$. It can be further shown that when these expressions are rationalized the resulting denominator which determines whether or not self-excitation will exist will be the same. This means therefore that the results presented in the paper apply equally well for small changes in the field excitation voltages, as well as for changes in the armature voltage.

Synchronous Machine With Solid Cylindrical Rotor

Discussion of a paper by C. Concordia and H. Poritsky published in the January 1937 issue, pages 49–58, and presented for oral discussion at the synchronous machinery session of the winter convention, New York, N. Y., January 27, 1937.

S. B. Crary (General Electric Company, Schenectady, N. Y.): This paper represents a valuable contribution to the theory of synchronous machines in that the effect of eddy currents in the main flux path of the solid rotor are included in the general equations. This makes possible more accurate analyses than have heretofore been made of the effect of the solid rotor on the short-circuit current, the torque slip characteristics, running out of and pulling into step, etc. Additional information as to the effect of saturation is also made available as the authors included the permeability of the rotor as one of the factors entering into their equations. The mathematical analysis of the effect of rotor eddy currents and main-flux saturation which the authors have made was essential in order that a better qualitative and quantitative understanding of the transient phenomenon involved in solid rotor synchronous machines be obtained.

The short-circuit current of turbogenerators has been calculated for some time based on rather empirical design constants which when compared with test data have not always checked very well. The reasons for these differences have been properly attributed to the difficulty in evaluating the effect of magnetic saturation and eddy currents in the magnetic parts.

It now seems desirable to consider in the light of the work by Concordia and Poritsky the present status of the problem of the determination of the magnitude of short-circuit currents of solid cylindrical rotor machines. They have found that the effect of main rotor body saturation and eddy currents is comparatively small, indicating that saturation and eddy currents in the leakage paths must play a predominant part in reducing the effective reactance to short circuit currents. In this analysis they assumed constant rotor permeability, an assumption which is likely to be questioned because the density actually may vary considerably. The importance of this assumption of constant permeability on the main flux path and the relative effect of leakage flux to main flux saturation may be more reasonably evaluated now on the basis of neglecting the effect of eddy currents, since Concordia and Poritsky have shown the relative unimportance of this factor in determining the short circuit current.

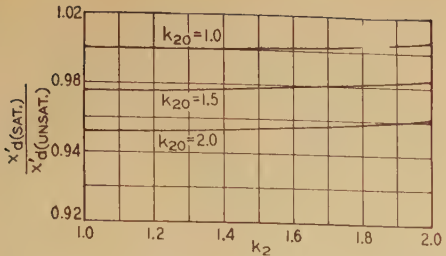


Figure 1. Effect of rotor main-flux saturation

If the effect of eddy currents is neglected, the comparative effect of main and leakage flux saturation can be approximately evaluated by equation 10 of a discussion given on page 1114 of the 1935 AIEE TRANSACTIONS. This equation is:

$$x_d'{}_{(sat.)} = 2 \times \frac{\left(\frac{x_{afd}}{k_2} + x_l\right)\left(\frac{x_{afd}}{k_2} + \frac{x_{fld}}{k_3}\right) - \frac{x^2_{afd}}{k_2^2}}{\frac{1}{k_{20}}\left[\frac{x_{afd}}{k_2} + \frac{x_{fld}}{k_3}\right] + \frac{1}{k_2}\left[\frac{x_{afd}}{k_{20}} + \frac{x_{fld}}{k_{30}}\right]} \cdot \frac{1}{k_{20}}$$

k_2 = rotor main-flux saturation factor
k_3 = rotor leakage-flux saturation factor
k_{20} = rotor initial main-flux saturation factor
k_{30} = rotor initial leakage-flux saturation factor

Refer to the above mentioned discussion for more complete definitions of this and the remaining quantities.

Figure 1 of this discussion shows the ratio between $x_{d(\text{satd.})}$ as calculated by this equation to $x_{d(\text{unsat.})}'$ for the case when the leakage saturation is zero ($k_{30} = k_3 = 1.0$) for different conditions of initial saturation in the rotor main flux path ($k_{20} = 1.0, 1.5, 2.0$), while the saturation at the instant of maximum armature reaction varies ($k_2 = 1.0$ to 2.0). As shown by these results, the initial saturation in the main flux path has only a small effect, while changes in saturation from the initial to the value at the instant of maximum armature reaction has a still smaller effect. The magnitude of the effect of the initial saturation in the main flux path checks very well the results obtained by Kilgore ("Effects of Saturation on Machine Reactances," AIEE TRANSACTIONS., volume 54, pages 545–50, May 1935) and by Concordia and Poritsky for the laminated-rotor case. The additional fact, indicated by figure 1, that the effect of the change in rotor main-flux saturation is very small and tending to increase the effective reactance checks physical reasoning and further justifies the assumption of Concordia and Poritsky of constant permeability in the main flux path. Physically, increased saturation in the main flux paths under short-circuit conditions is due to an increase in density due to a required increase in the total flux near the base of the rotor teeth in the direct axis in order that constant field flux leakages be maintained. This interesting fact was pointed out sometime ago by Mr. P. L. Alger. Although this increase in density may increase the saturation in the rotor, it results in a very small increase in the effective transient reactance. This probably can be noticed more decidedly by its effect to increase the a-c component of induced field current rather than its effect on the magnitude of short-circuit current, the short-circuit current being limited chiefly by the leakage flux. Therefore, the conclusion is reached that the effect of rotor main-flux saturation on the magnitude of armature short-circuit current is small and that the effect of leakage-flux saturation is the important factor which should be further investigated.

Accordingly, letting $k_2 = k_{20} = 1.0$ in equation 1 and investigating the effect of changes in initial leakage saturation ($k_{30} = 1.0, 2.0$) and changes in leakage saturation at the instant of maximum armature reaction ($k_3 = 1.0$ to 4.0), the results shown in figure 2 of this discussion were obtained. It is seen from these results that the effect of saturation in leakage paths is appreciable.

These results indicate the very decided effect of saturation in the leakage flux paths in reducing the effective reactance, while very little effect is produced by saturation in the main flux path.

Because of the importance of saturation in the leakage flux paths on the short-circuit current, a possible explanation for the apparently inconsistent results sometimes obtained when attempting to obtain the transient and subtransient reactances from the oscillographic records presents itself. Maximum leakage flux exists when the rotor has moved 180 degrees after the instant at which the 3-phase short circuit was applied, this leakage flux decreasing to a minimum value at 360 degrees and then rising to a slightly reduced maximum value at 540 degrees, etc., until the d-c armature transients have died out. Therefore, if the envelope of the completely offset wave of armature current is measured, this effect will tend to yield lower values of short-circuit reactance than the envelopes which are not completely offset. If a completely offset wave is not obtained, the lowest possible value of short-circuit reactance may not be obtained. This leakage flux, which pulsates with respect to the rotor, disappears with the decay of the d-c components of armature current, so that if the d-c components of armature current have disappeared, the magnitudes of the envelopes of the different phases should be approximately equal and the saturation in the leakage paths considerably reduced even for the case of a long field time constant.

This suggests a modification of our present manner of defining and measuring subtransient and transient reactance of turbogenerators. Possibly, we should use the terms "maximum possible 3-phase short-circuit current" to apply to the first peak of the completely offset current wave and "transient symmetrical short-circuit current" to apply to the component of short-circuit current obtained from extending the slowly decaying components of armature current, after the d-c component of armature current has decayed, back to the zero time axis. These 2 values of current could have their corresponding values of reactance. The reactance determined after the d-c components of armature current had decayed could be used in calculating system short circuits where the d-c time constant is very small, which is practically true every place except on or just off a generator bus. This reactance could also be used in stability calculations.

The value of reactance used for determining "the maximum possible short-circuit current" could be used for determining the maximum short-circuit currents near or at the generator terminals. This method would have the advantage of giving more accurate answers and a clearer conception of the actual effect of saturation on the short-circuit current.

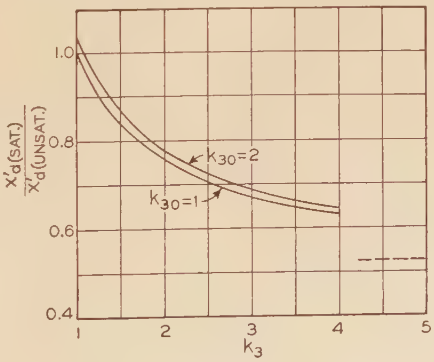


Figure 2. Effect of rotor leakage-flux saturation

Contributions to Synchronous Machine Theory

Discussion and author's closure of a paper by A. S. Langsdorf published in the January 1937 issue, pages 41–48, and presented for oral discussion at the synchronous machinery session of the winter convention, New York, N. Y., January 27, 1937.

S. B. Crary (General Electric Company, Schenectady, N. Y.): Dean Langsdorf has presented an interesting paper which gives methods of obtaining the steady-state characteristics by graphical constructions. Such constructions have the advantage in that the work involved in calculating the steady-state performance of a machine may be materially decreased. The work that Dean Langsdorf has done suggests a further step, that of taking saturation more completely into account by modifying the present constructions based on no saturation. This would make the results considerably more practical as the steady-state performance of a machine is affected appreciably by saturation in the magnetic circuit under many normal and particularly under certain abnormal operating conditions. The effect of saturation on the steady-state performance is, in general, a more important factor than the effect of saliency.

If the effect of saturation is to be considered it is suggested that the assumptions in regard to it be critically reviewed. Saturation in the armature core is not negligible and there may arise conditions of operation in which saturation in the pole tip cannot be neglected. Dean Langsdorf presents in figure 16 a method for modifying V curves to account for the effect of saturation. This modification tacitly assumes that saturation in the field poles is only a function of the field excitation while actually saturation in the field poles is a function of the flux in the pole which is dependent on both the armature and field magnetomotive forces and not the field magnetomotive force alone.

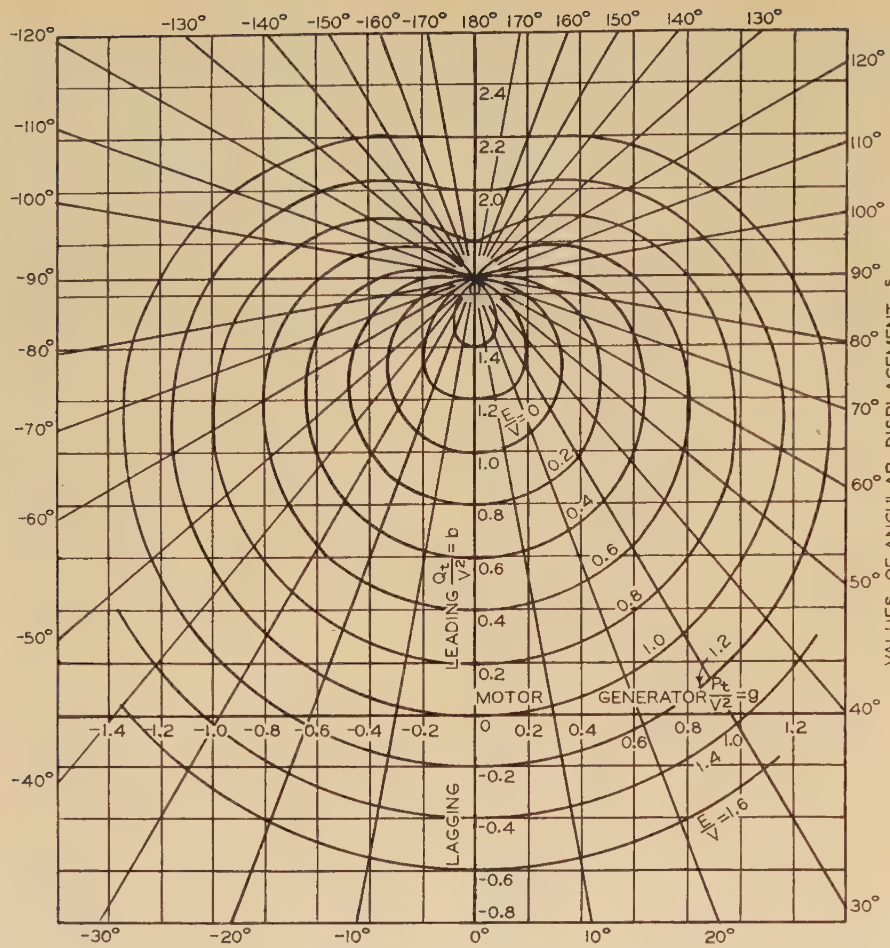


Figure 1. Chart for a salient-pole synchronous machine

$R_a = 0 \quad X_d = 1.00 \quad X_q = 0.60$

H. E. Edgerton and **Charles Kingsley, Jr.** (Massachusetts Institute of Technology, Cambridge): The writers, in collaboration with Professor W. L. Sullivan (now at Stevens Institute of Technology) developed several years ago a power chart for salient-pole synchronous machines which is very similar to the current chart, figure 10, of Professor Langsdorf's paper. The chart is illustrated in figure 1 of this discussion. The rectangular co-ordinates are

$$\frac{\text{power at the machine terminals}}{V^2} = \text{apparent conductance } g$$

= active component of armature current per-unit terminal voltage,

and

$$\frac{\text{reactive volt-amperes at the terminals}}{V^2} = \text{apparent susceptance } b$$

= reactive component of armature current per-unit terminal voltage.

Positive values of power are for generator action. Positive values of reactive volt-amperes are for leading-current generator action, or lagging-current motor action. The curves show the relation between the apparent conductance and susceptance for various constant values of the ratio E/V. The radial lines show various constant values of the load angle δ. The chart shown is drawn for a machine having the following constants:

$R_a = 0$
$X_d = 1.0$ per unit
$X_q = 0.6$ per unit

The reactances are assumed to be constant, independent of saturation. This same assumption is made by Professor Langsdorf. Although resistance has been neglected in drawing this chart, it is not a difficult matter to include resistance, as will be shown subsequently in describing the method by which the chart is drawn. Practically, the effects of the resistance of the machine are usually very small.

This chart is very much like figure 10 of Professor Langsdorf's paper. In fact, if figure 10 of the paper were rotated counterclockwise through 90 degrees, and the scale altered by dividing by the terminal voltage V, Professor Langsdorf would have obtained exactly these same curves for this machine. The advantage of altering the scale in this manner is that the chart now shows the vector loci of the armature current per unit terminal voltage. The chart can now be used at any terminal voltage, by correcting the readings taken from it in accordance with whatever the terminal voltage may be. This is a simple matter of multiplication. In addition to the curves for constant values of the ratio E/V, radial lines are drawn which show constant values of the load angle δ.

The only essential differences between this chart and figure 10 of Professor Langsdorf's paper are the change of scale, making the chart applicable at any terminal voltage (saturation being neglected), and the addition of the radial angle lines. This chart can be used, as shown by Professor Langsdorf, to obtain practically any of the normal steady-state operating characteristics of the machine.

The chart is constructed by a different method than that used by Professor Langsdorf. The procedure is shown in figure 2 of this discussion. In this construction the armature resistance is included. The construction is as follows:

Compute the co-ordinates of the point A, which are

$$g = -\frac{R_a}{R_a^2 + X_q^2}$$

$$b = +\frac{X_q}{R_a^2 + X_q^2}$$

Draw the line OA, connecting point A with the origin. Except for the change in scale and the rotation of the chart through 90 degrees, this line is the same as line OC of Professor Langsdorf's figure 9 extended to the point A where line OC again intersects the reluctance circle.

Draw the perpendicular bisector of OA and find point G, its intersection with the b-axis. The distance OG should be equal to $^1/_2\, X_q$.

Draw the axis of symmetry AGB.

Draw the reluctance circle ALC with its center O' on the axis of symmetry AGB and with its diameter equal to

$$\frac{X_d - X_q}{R_a^2 + X_d X_q}$$

Except for the change in scale, this is the same circle shown in figure 9 of the paper.

Draw in a number of radial lines ALP, AL_1P_1, etc., radiating from point A. These are the lines of constant load angle δ. The load angle is equal to the angle which these lines make with the zero angle line AO.

From the intersections L, L_1, etc., of the angle lines with the reluctance circle, measure the distance LP, L_1P_1, etc., equal to

$$\frac{E}{V}\,\frac{Z_q}{R_a^2 + X_dX_q}, \text{ where } \frac{E}{V} \text{ is a chosen value.}$$

Draw the curve connecting points P, P_1, P_2, etc. This is the admittance locus for the particular chosen value of E/V.

By repeating this comparatively simple graphical construction for other chosen values of E/V, the complete chart can be constructed.

It can readily be shown by simple geometry that the points L, L_1, etc., are the same as the corresponding points which would be obtained by Professor Langsdorf's graphical construction.

Mathematically, the curves are limaçons, symmetrical about the line AB, and having the polar equation

$$\rho = a + b \cos\theta$$

where a and b are constants.

There have also been several articles

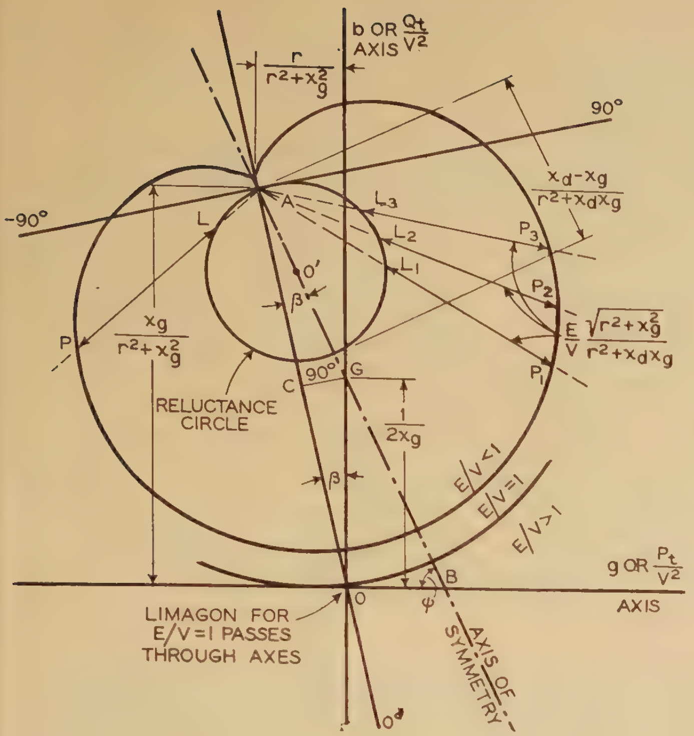


Figure 2. Construction of the chart

published in German ("Das Stromdiagramm der Synchronmaschine mit Ausgeprägten Polen in Symbolischer Behandlung," by Johannes Schammel, *Archiv für Elecktrotechnik*, volume 23, 1929, page 237). This article also gives a bibliography which may be of interest to those following the subject.

Sterling Beckwith (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.): The relations and curves derived by Mr. Langsdorf are very interesting, and probably answer questions which have been wondered about by everyone who has worked with synchronous machines for any appreciable length of time.

There are 2 interpretations of the term "equivalent" impedance. One is the reactance which can be used to replace the varying reactance of a machine and which has the value that will give correct power limits for the machine when used with constant internal voltages in the usual formulas for power limits. Another is the reactance which will give the correct internal voltage of a machine. A point worth mentioning in connection with the 2 definitions, both of which appear in the literature on the subject, is that the first reactance will not give correct internal voltages, and that the second reactance will not give correct stability limits. In order to get correct stability results with the latter type of reactance, for example, it is necessary not only to take into account the magnitude of the reactance but also its rate of change and the rate of change of the internal voltage. Both reactances are useful for their purposes, but their shortcomings must not be overlooked.

Two questions occur to me after reading the article. One is whether the power circles in figure 10 are true circles, or whether they approximate circles as in the case of the circles for constant internal voltage E. The other is whether the assumption of negligible tooth saturation and the use of the no-load saturation curve in figure 16 are sufficiently accurate in view of the fact that stability is dependent on the rate of change of saturation.

A. S. Langsdorf: The excitation loci of figure 10, and their Cartesian representation in the manner indicated in figure 12, have been checked experimentally by slip tests made with a small 15-kva laboratory alternator. The accompanying oscillograms, all made by the usual slip-test method show the results of slip tests with zero excitation (curve number 9); with very small excitation (curve number 10); and with a larger, but less than normal, excitation (curve number 11).

In the case of oscillogram number 9, the theoretical polar current locus is the small reluctance circle O' of figures 9 and 10. The current variation through the range from $\delta = 0$ to $\delta = 360$ degrees should theoretically show values of current which are less than the average through a range smaller than 180 degrees, and which are greater than the average through an angle of more than 180 degrees. This conclusion is amply supported by the oscillogram.

The second oscillogram, number 10, shows very clearly the humps predicted by figure 12 of the paper; and oscillogram number 11 shows how these humps are leveled with increasing excitation, and with the asymmetry to be expected because of the fact that the excitation loops of figure 10 extend below the zero-power circle more than they rise within it.

It is a further fact that the maximum power that can be developed by an unexcited motor (indicated by circle P_1, figure 10) is equal to the reluctance power

$$\frac{V^2(X_d - X_q)}{X_dX_q}$$

which appears as the coefficient of the second term of the coupling factor (equation 44), provided the resistance R_a is neglected. The proof of this statement follows readily from the equations given in the paper.

There is no doubt that a critical study of the effect of saturation, as suggested by Mr. Crary, would be useful to designers, but it is nevertheless true (quoting from the original paper) that "the full effect of saturation of the magnetic circuit is apparently beyond the scope of any reasonably simple analysis." It was believed that such an open disclaimer, serving as an introduction to the "reasonably simple" construction of figure 16, constituted sufficient notice of the approximate nature of that construction. As a matter of fact, the approximations involved in figure 16 are precisely the same as those suggested in appendix D (part I) of Doherty and Nickle's paper,[1] (footnote refers to numbered references in the article) and which are there shown as modifications of the vector diagram, whereas the present author chose to represent them as modifications of the derived V curves. Mr. Crary is quite correct in his contention that saturation is not a function of field excitation alone; it is decidedly a function of the armature current and the phase displacement between current and voltage. If anyone knows how to bring these additional factors into the picture he has a clear field; pending the presentation of a complete analysis, it may merely be said that the method embodied in figure 16 tends in the right direction. In any case, the purpose of the paper was not to emphasize saturation effects, but (quoting from the opening paragraph of the paper) "to point out some features . . . which follow . . . from the 2-reaction theory." That theory is completely represented by the vector diagram figure 4, and any shortcomings in the deductions are inherent in the theory itself.

It is interesting to note that the method of Messrs. Edgerton and Kingsley leads to the same conclusions as those of the paper under discussion, though their analysis stops short of such deductions as those concerning the law of variation of reactance, the nature of the V curves, etc.

Mr. Beckwith mentions 2 different interpretations of the term "equivalent impedance," both of which refer to single-valued quantities. As the term is used in the paper, it refers to a variable impedance which is a function of the 2 constant reactances, X_d and X_q, and of the variable phase angle ψ.

Mr. Beckwith raises the question whether the power circles of figure 10 are in reality true circles. Inasmuch as these circles are merely the geometrical representations of equation 1, the question is equivalent to asking (a) whether the power developed by the machine is really equal to the input minus the copper loss, and (b) whether the voltage V and the current I are the simple harmonic functions of time that they are tacitly assumed to be. The truth of (a) cannot be questioned, hence if (b) is satisfied the loci are truly circular, but with the understanding that P represents power developed, not power usefully delivered at the shaft. The second question, concerning tooth saturation, has already been implicitly answered in reply to Mr. Crary; the method of figure 16 is confessedly somewhat approximate, that is, qualitative rather than quantitative.

News

Of Institute and Related Activities

Pacific Coast Convention Includes All-Day Trip to Grand Coulee

TO THOSE who have looked forward to the time when they might profitably visit the Pacific Northwest, the 1937 AIEE Pacific Coast convention to be held in Spokane, Wash., August 31–September 3, offers an excellent opportunity to combine business with pleasure. Not only is the city of Spokane itself a recreational center, but also within easy reach are many fine trout streams and mountain lakes, and several famous national parks.

A special feature of the high-class technical program that has been arranged is a joint session with the Institute of Radio Engineers, which organization is concurrently holding its first Pacific Coast convention. Other attractions include an all-day inspection trip to the Grand Coulee project on the Columbia river, and the usual sports competitions and special entertainment.

Spokane a Recreational Center

A mountain river flows through the center of Spokane, and a big proportion of its banks has been, and is being, converted into State and City park areas. City and adjacent State parks total 4,920 acres, which is said to be the largest park area per capita of any city in the United States. Five golf courses, play grounds, the sunken gardens of Manito, all provide pleasant recreation.

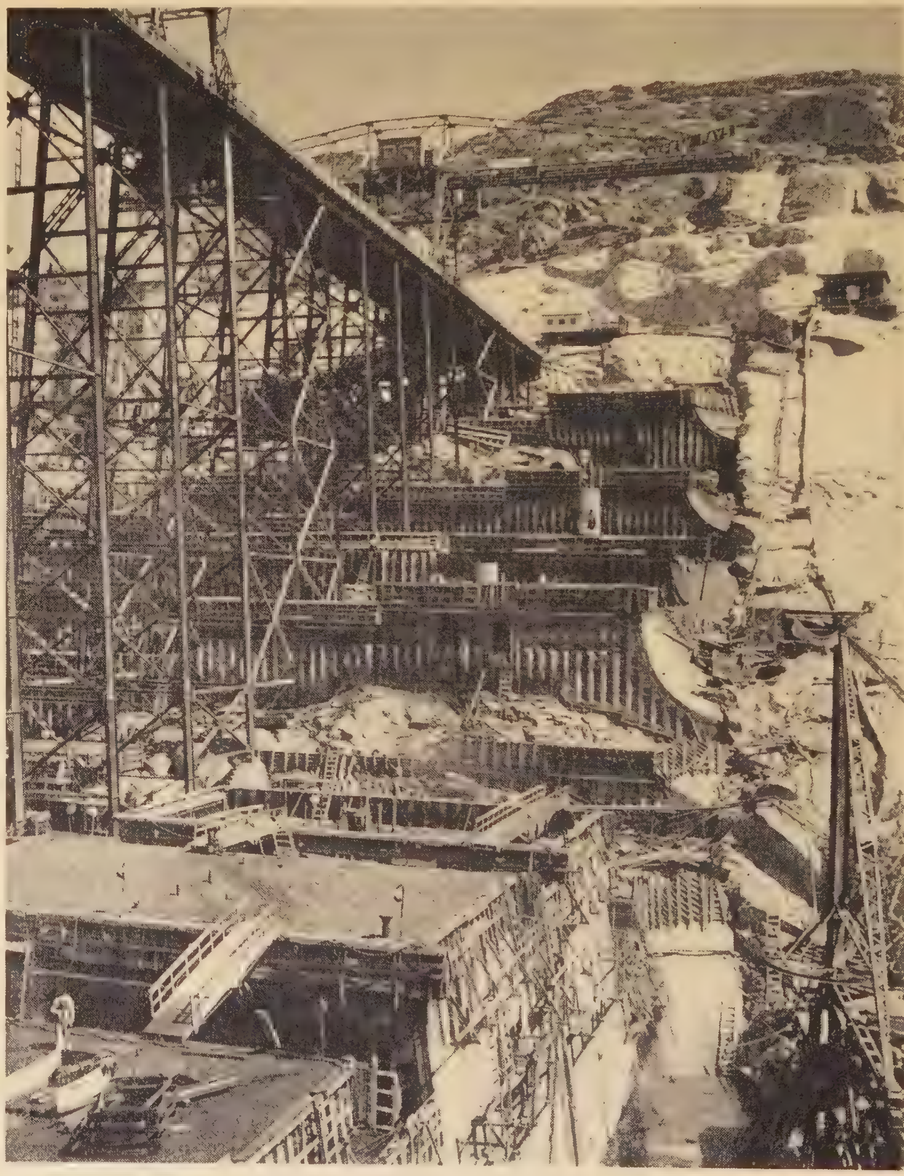
For those who will combine either all or part of their vacations with attendance at the convention, Spokane offers a surrounding recreational area of mountain scenery, fine trout streams, and lakes. Within 50 miles of Spokane are located 76 clear mountain lakes. Only a little farther away is the famous Coeur d'Alene mining district with the Sunshine Mine, the Bunker Hill Smelter, and other new and old producers. Only a little farther, and all within easy reach of Spokane, are the national parks, Glacier, Yellowstone, Craters of the Moon, Mount Rainier, Mount Baker, and others.

Technical Program

The technical program is comprised of a wealth of material, and some of the papers will deal with recent problems in the Pacific Northwest. Five technical sessions and one conference session on electric house heating will be held. The communication session will be a joint session with the Institute of Radio Engineers and papers also will be presented by well-known members of the IRE. According to F. E. Terman (A'23, M'34) of Stanford University, Calif., chairman of the IRE convention committee, present tentative plans call for a 2-day IRE convention to be held September 1 and 2 in the same hotel as the AIEE convention. Registration will be on the morning of September 1, followed by a technical session that afternoon. The jointly sponsored session is scheduled for Thursday morning and will be followed by another IRE session in the afternoon. The joint session and the IRE convention should prove an additional attraction for electrical engineers.

Interesting Inspection Trips

As a special feature, it is planned to devote one entire day to an inspection of Grand Coulee, the world's greatest dam, and an address on its electrical features by Alvin F. Darland of the United States Bureau of Reclamation. This dam, which



Blocks rising on the east abutment of Coulee Dam. The top of the dam is to be some 300 feet above the top of the trestle shown. Openings to the inspection and grouting galleries may be seen in some of the blocks. Approximately 500 cubic yards of concrete are used for a 5-foot lift on each block

being built for the dual purpose of irrigation and of power generation, is of great interest to all engineers. Grand Coulee is only 92 miles from Spokane.

What is said to be the world's tallest unguyed radio tower, which has just been completed in Spokane by station KHQ, also is on the inspection-trip program. The main tower is 803 feet tall with a short wave and television spire extending up to a total height of 828 feet.

Another "world's greatest" scheduled for inspection is the new pumping plant of the City of Spokane. Each of the 2 vertical turbine-type pumps is driven by a 900-horsepower 1,200-rpm vertical hollow-shaft motor built into the pump head, largest ever built of this construction.

Some Facts Concerning Grand Coulee

The Grand Coulee project, perhaps the most extensive of its kind every attempted, embraces the construction of a dam, power plant, and pumping plant on the Columbia River; a reservoir in Grand Coulee; and main irrigation canals and water distribution system on the project lands. The estimated cost of the dam and power plant is $178,790,000; of the irrigation system, $197,841,000. The dam is of the straight gravity type and will rise to a height of 550 feet, second only to Boulder Dam which is 727 feet. Thickness of the dam at the base will be about 500 feet and at the top about 30 feet. Length along the crest will be approximately 4,200 feet.

Some 11,250,000 cubic yards of masonry and 65,000,000 pounds of reinforcing steel will be required for the dam, power plant, and appurtenant works. The reservoir created by the dam will cover an area of about 82,000 acres and will contain approximately 10,000,000 acre-feet of water.

There will be 2 power houses, one at each end of the dam, each about 765 feet long. Ultimately, 18 generating units will be installed, each consisting of a 150,000-horsepower vertical turbine and a 120,000-kva 60-cycle 13,800-volt generator. Water will reach the turbines through 18 penstocks, each 18 feet in diameter, under an average head of 335 feet.

The pumping plant, which ultimately will contain 12 pumps each having a capacity of 1,600 cubic feet per second and driven by a 65,000-horsepower motor, will be on the west bank of the river adjacent to the upstream side of the dam. Normal pumping head will be 295 feet; maximum, 367 feet. Water from this pumping plant will be used to irrigate about 1,200,000 acres of land on the east side of the Columbia river.

The entire project is being constructed by the United States Government under the direction of the Bureau of Reclamation of the Department of the Interior. Excavation was begun in December 1933, and the placing of concrete in December 1935. If the present rate of progress is maintained, the dam and power plant will be completed in 1941. Initially, only 3 generating units will be installed; these are expected to be in operation during 1942. Present plans provide for bringing in irrigation areas in small units only, at such times as there is a demand for additional land. According to estimates, the irrigation project will be finally completed at the end of about 40 years.

Sports

As usual, the high light of the sports events will be the golf tournament for the John B. Fisken cup. An interesting feature of the sports program this year is that Mr. Fisken himself, a resident of Spokane, is chairman of the convention's sports subcommittee. A variety of other competitions will round out the sports program.

Special Entertainment for Women

For the women guests at the convention, one of the most interesting features will be the gardens of Spokane. During 4 years of participation in the nationwide contest of the National Yard and Garden Contest Association of America, Spokane gardens have won 4 first prizes. This is said to be more "firsts" than have been won by any other American city—in fact, as many as ever have been won by all the gardens within any other entire state.

Tentative Program

In this program, reference to the issue and, in so far as possible, to the page in ELECTRICAL ENGINEERING is given for all papers

Tuesday: August 31

10:00 a.m.—Opening of Convention

10:15 a.m.—Selected Subjects

Lighting the San Francisco-Oakland Bay Bridge, C. R. Davis, Department of Public Works, State of California. Scheduled for August issue

Present Day and Probable Future Electrical Applications in Aircraft, W. V. Boughton, Douglas Aircraft Company, Inc. Scheduled for August issue

Proposals for the Administration of Federal Power in the Pacific Northwest, H. V. Carpenter, State College of Washington. Scheduled for August issue

2:00 p.m.—Development of Protective Equipment

Relay Operation During System Oscillations, C. R. Mason, General Electric Company. July issue, pages 823–32

A Comprehensive Method of Determining the Performance of Distance Relays, J. H. Neher, Philadelphia Electric Company. July issue, pages 833–44

The Ultra-High-Speed Reclosing Expulsion Oil Circuit Breaker, A. C. Schwager, Pacific Electric Manufacturing Corporation. Scheduled for August issue

Capacitance Control of Voltage Distribution in Multi-Break Breakers, R. C. Van Sickle, Westinghouse Electric & Manufacturing Company. Scheduled for August issue

9:00 p.m.—Reception and Informal Dance

Wednesday, September 1

9:00 a.m.—Power Transmission and Distribution

Empirical Method of Calculating Corona Loss From High-Voltage Transmission Lines, J. S. Carroll, Stanford University, and Mabel Macferran Rockwell, consulting electrical engineer. May issue, pages 558–65

Distortion of Traveling Waves by Corona, H. H. Skilling, Stanford University, and P. de K. Dykes, Cambridge (England) University. July issue, pages 850–7

Analysis of Series Capacitor Application Problems, J. W. Butler and C. Concordia, General Electric Company. Scheduled for August issue

2:00 p.m.—Student Technical Session

—Golf

8:00 p.m.—Banquet; Presentation of Prizes

Thursday, September 2

9:00 a.m.—Joint Communication Session With Institute of Radio Engineers

Magnetic Generation of a Group of Harmonics, Eugene Peterson, J. M. Manley, and L. R. Wrathall, Bell Telephone Laboratories, Inc. Scheduled for August issue

Radiotelephone Noise Reduction by Voice Control at Receiver, C. C. Taylor, Bell Telephone Laboratories, Inc. Scheduled for August issue

The Vodas, S. B. Wright, Bell Telephone Laboratories, Inc. Scheduled for August issue

Transmission Lines at Very High Radio Frequencies, L. E. Reukema, University of California. Scheduled for August issue

The Developmental Problems and Operating Characteristics of 2 New Ultrahigh-Frequency Triodes, Winfield G. Wagener, RCA Radiotron Company. IRE paper

High-Efficiency Grid-Modulated Amplifiers, F. E. Terman and John Woodyard, Stanford University. IRE paper

2:00 p.m.—Student Technical Session

—Session on Electrical Machinery

Tooth-Frequency Eddy-Current Loss, Paul Narbutovskih, Stanford University. February issue, pages 253–56

The Saturated Synchronous Machine, B. L. Robertson, T. A. Rogers, and C. F. Dalziel, University of California. July issue, pages 858–63

Transformer Current and Power Inrushes Under Load, E. B. Kurtz, University of Iowa. Scheduled for August issue

8:00 p.m.—Conference on Electric House Heating

Electric Heating of Residences, C. E. Magnusson, University of Washington.

Electric Heating of Residences, H. V. Carpenter, State College of Washington.

Friday, September 3

Coulee Dam Trip

Address: The Coulee Dam Project, Alvin F. Darland, United States Bureau of Reclamation.

Lobby of the Davenport Hotel, Spokane, Wash., headquarters of the AIEE 1937 Pacific Coast convention

There will be sight-seeing trips for the women, a bridge luncheon at the Country Club, golf, putting contests, and other entertainment.

Hotels and Registration

Convention headquarters will be at the Davenport Hotel where registration desks will be open from early Tuesday morning, August 31. Accommodations of all types are available at the Davenport at prices beginning at $3 per day.

Accommodations at the Spokane Hotel will range from $2 to $6. The Desert Hotel, across the street from the Davenport, and the Coeur d'Alene have accommodations ranging from $2.50 upward. All members desiring accommodations are urged to make their reservations early. Special arrangements are being made for economical accommodations for Enrolled Students.

Committees

In the following list are given the members of the 1937 Pacific Coast convention committee, which includes the 10 subcommittee chairmen, as indicated.

H. V. Carpenter, *chairman*
R. D. Sloan, *vice-chairman*
M. F. Hatch, *secretary*

Reinier Beeuwkes	H. S. Lane
S. E. Caldwell	F. O. McMillan
J. B. Fisken	H. L. Melvin
L. R. Gamble	H. S. Osborne
J. C. Gaylord	George Quinan
C. R. Higson	C. E. Rogers
N. B. Hinson	R. W. Sorensen
R. H. Hull	A. Vilstrup

L. R. Gamble, meetings and papers
J. S. McNair, finance
L. A. Traub, transportation
H. W. Webbe, housing
J. R. Murphy, entertainment
J. B. Fisken, sports
H. B. Hodgins, publicity
R. H. Hull, student activities
D. H. Olney, registration
Earl Baughn, inspection trips

Electric Power Markets in Washington. This is the title of a 40-page bulletin (No. 93) of the University of Washington Engineering Experiment Station, prepared by Doctor C. E. Magnusson, professor of electrical engineering at the university, and director of the Engineering Experiment Station. This bulletin presents, largely in tabular and graphical form, the results of an extensive study of the electric heating of residences in Seattle. It is listed as being available from the University at 40 cents per copy.

AIEE Directors Meet at Institute Headquarters

The regular meeting of the board of directors of the American Institute of Electrical Engineers was held at Institute headquarters, New York, on May 24, 1937.

Present: *President*—A. M. MacCutcheon, Cleveland, Ohio. *Past-President*—H. P. Charlesworth, New York, N. Y. *Vice-Presidents*—C. V. Christie, Montreal, Canada; Mark Eldredge, Memphis, Tenn.; C. Francis Harding, Lafayette, Ind.; W. H. Harrison, New York, N. Y.; A. C. Stevens, Schenectady, N. Y. *Directors*—F. M. Farmer, New York, N. Y.; H. B. Gear, Chicago, Ill.; F. Ellis Johnson, Columbia, Mo.; C. R. Jones, New York, N. Y.; P. B. Juhnke, Chicago, Ill.; W. B. Kouwenhoven, Baltimore, Md.; Everett S. Lee, Schenectady, N. Y.; K. B. McEachron, Pittsfield, Mass.; C. A. Powel, East Pittsburgh, Pa.; R. W. Sorensen, Pasadena, Calif. *National Treasurer*—W. I. Slichter, New York, N. Y. *National Secretary*—H. H. Henline, New York, N. Y. Present by invitation during discussion of one item—Past-President A. W. Berresford, New York, N. Y.

Minutes were approved of meetings of the board of directors held January 26–27, 1937, and the executive committee on March 25, 1937.

Announcement was made of the vacancies in the board of directors caused by the deaths of Past-Presidents J. Allen Johnson and E. B. Meyer and the filling of these vacancies by Past-Presidents H. P. Charlesworth (to August 1, 1937) and J. B. Whitehead (to August 1, 1938), in accordance with the board's interpretation, in May 1936, of section 35 of the constitution to mean that the 2 most recent living past-presidents shall be members of the board of directors.

Actions of the executive committee on applications for admission, transfer, and Student enrollment were reported and confirmed, as follows: As of February 19, 1937—1 applicant elected and 5 applicants transferred to the grade of Fellow; 12 applicants elected and 13 applicants transferred to the grade of Member; 76 applicants elected to the grade of Associate; 81 Students enrolled. As of April 16, 1937—2 applicants transferred to the grade of Fellow; 6 applicants transferred and 11 elected to the grade of Member; 470 applicants elected to the grade of Associate; 68 Students enrolled.

Reports were presented and approved of meetings of the board of examiners held April 14 and May 12, 1937. Upon the recommendation of the board of examiners, the following actions were taken: 2 applicants were transferred to the grade of Fellow; 14 applicants were transferred and 27 were elected to the grade of Member; 342 applicants were elected to the grade of Associate; 164 Students were enrolled.

Monthly disbursements as follows were reported by the finance committee and approved: April, $18,714.91; May, $20,679.11.

Upon recommendation of the committee on electrophysics, the board authorized a change in name of that committee to "committee on basic sciences," without change in function.

Approval was given to a recommendation of the membership committee that each District vice-chairman of that committee be added to the executive committee of his geographical District, if not already a member of the executive committee in another capacity. The wording of revisions of sections 32 and 76 of the by-laws, to bring them into conformity with this policy, was referred to the committee on constitution and by-laws.

Approval was given to the appointment, upon nomination by the standards committee, of Institute representatives, as

Future AIEE Meetings

Pacific Coast Convention
Spokane, Wash., Aug. 30–Sept. 3, 1937

Middle Eastern District Meeting
Akron, Ohio, Oct. 13–15, 1937

Winter Convention
New York, N. Y., January 24–28, 1938

North Eastern District Meeting
Pittsfield, Mass., Spring 1938

Summer Convention
Washington, D. C., June 20–24, 1938

follows: T. H. Haines, on Sectional Committee on National Electrical Safety Code, and W. C. Goodwin, on Sectional Committee on Safety Code for Mechanical Refrigeration.

H. B. Gear was appointed an Institute representative on the Commission of Washington Award, for the 2-year term beginning August 1, 1937, to succeed L. A. Ferguson, whose term will expire at that time.

The board confirmed applications made by the AIEE committee on research to The Engineering Foundation for financial support for the year 1937–38 of the following research projects: investigation of electric shock, stability of impregnated paper insulation, and work of welding research committee.

Upon recommendation of the committee on research, it was voted "that the board approves in principle the idea of a contribution by the AIEE toward the specific research projects which the board recommends to The Engineering Foundation for financial support, of not more than $500 for any one project in a year, the total amount appropriated for all such projects during a budget year not to exceed one-half of one per cent of the total gross income of the AIEE for the preceding fiscal year."

Appointment by the president of the following committee of tellers to canvass and report upon the ballots for the election of Institute officers was approved: W. E. Coover (chairman), John T. Binford, George C. Brown, M. S. Mason, L. M. McCullough, L. A. Nelson, and A. M. Schoettgen.

A report, transmitted by Chairman F. B. Jewett of the committee on Iwadare Foundation, from E. H. Colpitts, covering his Iwadare lectureship itinerary in Japan in the spring of 1937, was received and ordered filed.

The report of the committee on award of Institute prizes, of the awards made by the committee for papers presented during 1936, was presented. (The report was published in the June issue of ELECTRICAL ENGINEERING, page 756.)

The annual report of the board of directors to the membership for the fiscal year which ended April 30, 1937, as prepared by the national secretary, was approved for presentation at the annual meeting of the Institute on June 21. This included reports in full or in abstract of general standing committees. The report appears elsewhere in this issue.

The annual report of the national treasurer was presented and approved.

In accordance with section 37 of the constitution, consideration was given to the appointment of a national secretary of the Institute for the administrative year beginning August 1, 1937; and National Secretary H. H. Henline was reappointed.

President A. M. MacCutcheon was appointed the official delegate of the Institute to the semicentennial of The Engineering Institute of Canada, June 15–18, 1937.

Other matters were discussed, reference to which may be found in this or future issues of ELECTRICAL ENGINEERING.

Honorary Members Named at Summer Convention

Election of Bion J. Arnold and Alex Dow to honorary membership in the AIEE was formally announced at the opening session of the Institute's 1937 Summer Convention, which is being held in Milwaukee, Wis., as this issue goes to press. These 1937 elections are the first since 1933 when 6 prominent engineers and scientists were so honored. Doctor Arnold has been an independent consulting engineer since 1893 and has been active in Institute affairs, having served as the 16th president (1903–04). Doctor Dow is a pioneer in the electric utility field and was awarded the AIEE Edison medal for 1936 for outstanding leadership in that industry. Biographical sketches of both men are given in the "Personals" columns of this issue.

Neither Doctor Dow, who is in Europe, nor Doctor Arnold was present at the ceremony. Doctor Arnold was injured in an automobile accident on June 19, the Saturday before convention week, while on his way home from hospital confinement resulting from an earlier accident. Honorary Member certificates were sent to Doctor Dow by D. H. Baker, convention delegate from the Detroit-Ann Arbor Section, and to Doctor Arnold by his son.

As specified in sections 8 and 9 of the Institute's constitution,

> Honorary Members may be chosen from among those who have rendered acknowledged eminent service to electrical engineering or its allied sciences.
>
> Honorary Members shall be proposed in writing by at least 10 members, and may be elected only by the unanimous vote of the board of directors, a ballot in writing to be forwarded by members absent from the directors' meeting. The election of an Honorary Member shall be deemed invalid if an acceptance is not received within 6 months after the date of his election.

The grade of honorary member is the highest in the AIEE, and since the founding of the Institute in 1884 has been granted to only 33 men, including Doctors Arnold and Dow. Of those elected prior to this year, only the following are still living: André E. Blondel, W. L. R. Emmet, Herbert Hoover, A. E. Kennelly, Guglielmo Marconi, R. A Millikan, Chas. F. Scott, and Motoji Shibusawa.

New Officers Elected

The report of the committee of tellers also was presented at the first session of the convention, and the following new officers were declared elected, each to take office August 1, 1937.

President:

W. H. Harrison, assistant vice-president, department of operation and engineering, American Telephone and Telegraph Company, New York, N. Y.

Vice-Presidents:

I. Melville Stein, director of research, Leeds & Northrup Company, Philadelphia, Pa.

Edwin D. Wood, general superintendent, Louisville Gas & Electric Company, Louisville, Kentucky.

L. N. McClellan, chief electrical engineer, U.S. Bureau of Reclamation, Denver, Colo.

J. P. Jollyman, hydroelectric and transmission engineer, Pacific Gas & Electric Company, San Francisco, Calif.

M. J. McHenry, manager, Toronto district, Canadian General Electric Company, Ltd., Toronto, Ont.

Directors:

C. R. Beardsley, superintendent of distribution, Brooklyn Edison Company, Inc., Brooklyn, N. Y.

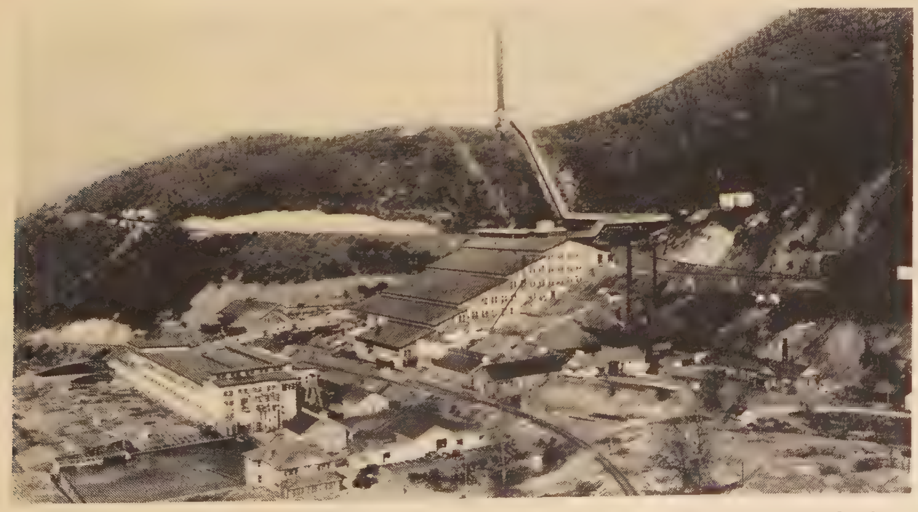
Vannevar Bush, vice-president and dean of engineering, Massachusetts Institute of Technology, Cambridge.

F. H. Lane, manager, engineering division, Public Utility Engineering & Service Corporation, Chicago, Ill.

National Treasurer:

W. I. Slichter, professor of electrical engineering, Columbia University, New York, N. Y.

The board of directors for the administrative year beginning August 1, 1937, consists of these newly elected officers, together with the following hold-over officers: A. M. MacCutcheon (retiring president), Cleveland, Ohio; J. B. Whitehead (junior past president), Baltimore, Md.; F. Malcolm Farmer, New York, N. Y.; N. E. Funk, Philadelphia, Pa.; H. B. Gear, Chicago, Ill.; F. Ellis Johnson, Columbia, Mo.; C. R. Jones, New York, N. Y.; W. B.



The electrolytic zinc plant of the Sullivan Mining Company, a 2- or 3-hour drive from Spokane, will be an attraction to those attending the Institute's 1937 Pacific Coast convention who are interested in the application of electricity to ore mining and refining

Kouwenhoven, Baltimore, Md.; K. B. McEachron, Pittsfield, Mass.; C. A. Powel, East Pittsburgh, Pa.; R. W. Sorensen, Pasadena, Calif.; A. C. Stevens, Schenectady, N. Y.; O. B. Blackwell, New York, N. Y.; C. F. Harding, Lafayette, Ind.; L. T. Blaisdell, Dallas, Tex.; C. E. Rogers, Seattle, Wash.

The first day's registration, which numbered 563 members and guests, presaged a highly successful convention. A detailed report of the various convention activities is scheduled for inclusion in the August issue.

New Name for Electrophysics Committee

The name of the AIEE committee on electrophysics has been changed to "committee on basic sciences" by authorization of the AIEE board of directors, following the recommendation of the committee. The function of the committee remains unchanged.

The electrophysics committee was organized in 1911. Its scope, as defined at the present time, is: "Treatment of all matters in which the dominant factor is electrophysics, and which are of such novel character as to be unapplied in any apparatus or field of application within the scope of the other technical committees, or which are of such generality as to be significant within the scopes of several technical committees. Such subjects as general circuit theory, electrostatics, mathematical treatises, magnetics, general electrical units, and nomenclature are properly within the scope of this committee."

Executive Committee of Pacific District Meets

A meeting of the executive committee of the AIEE Pacific District was held in the Engineers' Club at San Francisco, Calif., May 27, 1937. Members of the executive committee who attended were:

N. B. Hinson, vice-president, AIEE, Los Angeles

J. C. Gaylord, chairman, Los Angeles Section

E. F. Peterson, chairman, District committee on student activities, Santa Clara

H. S. Lane, chairman, San Francisco Section

F. S. Benson, secretary, San Francisco Section

Fred Garrison, secretary, AIEE Pacific District

Present by invitation:

R. F. Monges, executive committee, San Francisco Section

W. H. Evans, executive committee, San Francisco Section

C. V. Fowler, executive committee, San Francisco Section

E. M. Wright, executive committee, San Francisco Section

R. O. Brosemer, chairman-elect, San Francisco Section

J. P. Jollyman, nominee for vice-president AIEE

J. S. Carroll, member-elect of executive committee, San Francisco Section

Vice-President Hinson presided. As the first item of business, chairman Gaylord of the Los Angeles Section read the following letter which he had written to Chairman Lane of the San Francisco Section:

> At a recent meeting of the executive committee of the Los Angeles Section, it was unanimously voted that we should pledge to the San Francisco Section our wholehearted support in its effort to have San Francisco chosen as the convention city for the national summer convention of the AIEE in the year 1939.
>
> It was also voted that should you be successful in obtaining the convention that year, we would do everything in our power to help make the convention a success.

After the reading of this letter, the committee voted to go on record as being in favor of holding the Institute's 1939 summer convention in San Francisco.

Promotion of greater interest on the part of students in preparing papers for District Branch paper competition was discussed. It was believed that the student counselors were in best position to encourage the preparation of such papers. It was thought also that the closer co-operation of student relations members on the executive committees of neighboring Sections with the students would encourage the students to prepare papers.

The proposed method of *inviting* Institute members to become Fellows, rather than leaving to the members themselves the initiation of applications for transfer to that grade, was discussed. It was the opinion of the committee that this plan should be adopted.

Much discussion centered about the proposed professional engineers licensing act, which was defeated in the California State Assembly at Sacramento this year. It was reported that a committee has been appointed from the San Francisco Engineering Council, which will co-operate with a similar committee from the Los Angeles Engineering Council, to frame a bill licensing professional engineers for possible introduction into the Assembly at their 1939 meeting.

After adjournment, those present attended the regular dinner and monthly meeting of the San Francisco Section.

Electrical Industry Honors George Stickney

During a chef dinner given as part of the annual advanced lighting conference held recently at General Electric Institute, Nela Park, Cleveland, Ohio, tribute was paid by the electrical industry to G. H. Stickney (A'04, F'24) consulting engineer of the incandescent lamp department of the General Electric Company, Cleveland, in recognition of his numerous contributions to lighting progress during more than 40 years of service with the company. Formal presentation of an elaborate book in which the tribute was inscribed was made by E. E. Potter, eastern sales manager of the incandescent lamp department, in behalf of the hundreds of lighting men whose personal signatures the memento also contains. In the photograph reproduced above are shown John Arthur, Kansas City Power and Light Company; Ward Harrison (F'36) director of Nela Park engineering department; Mr. Stickney, examining his souvenir book; and Mr. Potter.

Schenectady Section Sponsors Steinmetz Museum

The Schenectady Section of the AIEE, believing that the home of Dr. C. P. Steinmetz, including his library, laboratory, and personal effects, should be preserved to serve as an inspiration for the engineers of all time, is participating with other groups in a campaign to secure funds for its purchase. This property, when acquired, will be converted into a memorial museum to serve as a showplace for all the worthy Steinmetz mementos available, and will provide a point of great interest for all visitors, particularly to electrical engineers. An invitation to participate in the establishment of the museum has been extended to friends of Steinmetz throughout the United States.

Membership—

Mr. Institute Member:

By bringing to the attention of your Section membership committee, the names of those who you feel are eligible for membership in the Institute, you help both the Institute and your fellow engineers.

Such co-operation on your part is very greatly appreciated by the Section membership committees.

John Backus

Vice-Chairman, District No. 9
National Membership Committee

This is the second activity to memorialize this noted electrical engineer to be engaged in by the Institute's Schenectady Section, the Steinmetz Memorial Lectures having been established by that Section in 1925. To date, 11 lectures in this series have been delivered, the last of which was published in the May 1937 issue of ELECTRICAL ENGINEERING, pages 510–17.

Student Conference Held by North Central District

The tenth annual conference of Student Branches of the AIEE North Central District was held at the South Dakota State College, Brookings, April 23–24, 1937. The conference included 2 technical sessions at which 8 papers by student authors and a demonstration lecture were presented, a banquet, and 2 business sessions of the Student Branch counselors in the District. Although the official registration numbered only 68, it was estimated that more than 100 persons attended the technical sessions. All 9 Institute Branches within the District were represented.

President A. M. MacCutcheon of Cleveland, Ohio, was present for the entire conference and participated actively in all the technical and business meetings. His interest and advice was said to be very helpful in making this one of the most successful student conferences ever held in the District. He was the principal speaker at the banquet.

The meeting was opened by AIEE Vice-President R. H. Fair of Omaha, Neb., who introduced President MacCutcheon and Doctor H. M. Crothers, dean of engineering of the South Dakota State College, who made an appropriate address of welcome. After the opening address the first technical session began with T. J. Anderson, chairman of the University of Nebraska Branch, presiding. Lester C. Corrington of the South Dakota State School of Mines Branch presided at the second session. The following papers were presented at these sessions:

ARC WELDING AND ITS APPLICATION IN THE INDUSTRY, by James Landmesser, South Dakota School of Mines, Rapid City.

ELECTRON FOCUSING, by R. P. Buckingham and E. Pekhonen, University of North Dakota, Grand Forks.

THE DEVELOPMENT OF SOUND PICTURES, by John McKendry, University of Wyoming, Laramie.

X-RAYS AND THEIR APPLICATIONS, by Charles B. Minnich, University of Nebraska, Lincoln.

THE LIFE OF CHARLES PROTEUS STEINMETZ, by Everett H. Lee, South Dakota State College, Brookings.

SUN AND WIND AS POWER GENERATORS, by Howard McAllister, University of Colorado, Boulder.

SOME INVESTIGATIONS ON ELECTRETS, by John J. Shideler and Alfred R. Lee, University of Denver, Colo.

NEWTON'S DEVELOPMENT OF THE CALCULUS, by Kenneth Frolund, North Dakota State College, Fargo.

In addition to the foregoing papers, a demonstration relating to inductive co-ordination was given by S. B. Hughes and I. M. Ellestad (A'24) of the Northwestern Bell Telephone Company and A. A. Little of the Dakota Central Telephone Company. In this demonstration a miniature transmission line paralleled by a miniature telephone line was employed, and the effect of various conditions on the amount of noise induced on telephone circuits paralleled by power circuits was illustrated. The effectiveness of transpositions in mitigating interference effects was very clearly demonstrated.

Counselors present at the 2 business sessions were: W. H. Gamble, Branch counselor chairman, AIEE North Central District, South Dakota State College; H. S. Rush, North Dakota Agricultural College; H. F. Rice, University of North Dakota; J. O. Kammerman, South Dakota State School of Mines; L. A. Bingham, University of Nebraska; H. B. Palmer, University of Colorado; and G. H. Sechrist, University of Wyoming. President MacCutcheon and Vice-President Fair also attended. Chairman Gamble, who presided, first gave a report of the discussions at the conference of officers, delegates, and members held during the Institute's 1936 summer convention at Pasadena, Calif. Upon formal invitation of Professor Bingham, it was voted that next year's conference be held at the University of Nebraska, Lincoln. Following the usual custom, Professor Bingham then was elected District Branch counselor chairman for the coming term.

Concerning the conduct and scheduling of future student conferences, the following actions were taken:

1. Time allowed for delivering student papers is to be limited to 20 minutes each.

2. Each paper is to be discussed immediately following its presentation.

3. Discussions of student papers are to be limited to students, and the time allowed each discusser is to be limited to 10 minutes.

The proposition of obtaining an outside speaker for the annual conference was discussed and was viewed with favor. T. H. Granfield of Omaha, Neb., secretary of the AIEE North Central District, acted as secretary of the conference.

Electrical Reports at NFPA Meeting

At the forty-first annual meeting of the National Fire Protection Association, held in Chicago, Ill., May 10–14, 1937, reports were presented by the electrical committee and by committees on static electricity and protection against lightning. H. S. Warren (A'03, F'13) attended the meeting as Institute representative on the electrical committee of the association, and the following information was received from him.

The report of the electrical committee, A. R. Small, chairman, was a summary report outlining the more important changes in the National Electrical Code which were adopted by the committee in March 1937. A minority report was submitted, but this did not prevent the acceptance of the electrical committee's report. The issue raised by the minority report was whether the use of a nontamperable type of plug fuse should be mandatory after July 1, 1937. The electrical committee's attitude was that such mandatory requirement would be premature because of the patent situation and because satisfactory types of nontamperable fuses embodying interchangeability have not yet been made available. Another item in the electrical committee's report which received extended discussion had reference to the classification of pyroxylin plastic manufacturing plants in respect to hazardous locations. The 1937 edition of the code will contain many changes, and will have an entirely new format and editorial arrangement.

The committee on static electricity, P. V. Tilden, chairman, presented a report consisting of 44 printed pages of text and diagrams. Sparks from static electricity constitute a very serious hazard where flammable liquids or gases are present. In many kinds of manufacturing establishments flammable or explosive materials are

involved, so careful safeguarding against sparks is essential. The report tells how accumulations of static electricity can be prevented most effectively by the interbonding and thorough grounding of all metal pipes, containers, and other equipment.

The report of the committee on protection against lightning, M. G. Lloyd (A'08, F'12) chairman, was devoted principally to an additional section covering the protection of reinforced concrete stacks. A similar addition was approved by the sectional committee on protection against lightning of the American Standards Association, which held a joint session with the NFPA on one of the days during the meeting. Doctor Lloyd is chairman of both committees, and Mr. Warren is a member of the ASA committee.

National Adequate Wiring Program. Appointments to a national adequate wiring committee have been completed, according to a recent issue of "Nema News," and the committee will now proceed to consider the details for the national adequate wiring program initiated by the National Electrical Manufacturers Association. The broad purpose of the program is to educate the householder to recognize and meet the need for adequate electrical wiring. Members of the committee are: M. E. Skinner and C. A. Eastman (A'35), Edison Electric Institute; E. G. May and S. J. O'Brien, National Electrical Contractors Association; W. E. Sprackling and G. C. Thomas, Jr., NEMA; and J. S. Bartlett and George R. Conover, International Association of Electrical Leagues.

Current Items From American Engineering Council

Engineers' Public-Employment Trends

Engineering employment by government agencies in Washington is somewhat disturbed by the threats of both Congress and the Administration actually to apply economy measures. The President has ordered all departments, administrations, and commissions including the Bureau of the Budget materially to reduce current expenditures and to limit future operations to be budgeted within the national income. Congress seems to have accepted the President's advice, and to have set itself to the task of reducing federal expenditures. Allowing for the application of political expediency in yielding to "certain pressures," a substantial reduction in the flow of public funds through the "emergency agencies" for "work relief" and "pump priming purposes" appears more like a certainty than ever before.

As evidence of the acceptance of the seriousness of these intentions, "administrative executives" are advising capable associates to transfer to other work within government service or seek opportunities in private enterprise. Rural electrification and the more permanent agencies are absorbing some of the engineers. Others will be re-employed by special activities similar to "the building materials study" scheduled to be started by the Bureau of Standards in July but a distressingly large number of competent engineers are leaving government work with its uncertainties and meagre compensation for the increasingly attractive private life. In recognition of operating difficulties likely to develop as more of the better engineers return to private employment and practice, the Civil Service Commission is planning to conduct an unassembled examination for engineers of the several grades of a dozen branches of engineering at an early date. Although civil service cannot be made more attractive in either classification or compensation until there is new legislation in that direction, an effort is being made to raise educational and experience standards for each grade, with the hope that engineers better fitted for public service may be induced to qualify for the design, construction, operation, and maintenance of public property, and for research, educational, or advisory and supervisory or inspection duty in the several lines of accepted public service.

Without becoming involved in anything leading toward the socialization of engineering or the standardization of either duties or salaries which might limit engineering initiative, Council through its staff and committees, is aiding the Commission and its "engineer examiners" in their efforts to improve the engineer personnel under civil service. This opportunity to forward engineering recognition and to act indirectly for the improvement of the economic status of the engineer in public service, comes to AEC as an invitation from the Civil Service Commission. Council is thus accepted as an instrumentality of organized engineering in position to express the united opinion of engineers regarding the qualifications for and conditions of the employment of engineers by those arms of the federal government of the United States whose employees are under civil service. In that position, Council may well be a stabilizing influence against unionization. Council is also given an opening to act for the engineering profession to further the use of the merit system in preference to patronage and in the public welfare.

Government Reorganization

American Engineering Council has made its files available to both The President's Committee on Administrative Management and the Select Committee on the Investigation of Executive Agencies. Members of the staff have advised with both committees regarding the economies which might be attained by regrouping or reorganization of existing agencies. Council has also offered its services to the Joint Committee on Government Reorganization.

Each of the committees has studied Council's recommendation for the centralization of all public works under one qualified head and it is understood that ideas advanced by AEC have been incorporated in committee suggestions as representing the best thought on the subject available. None of the findings of the committees have been announced but all 3 committees are believed to have urged the creation of a public works department.

Four bills carrying the principal points in the President's reorganization program are scheduled for this session of Congress but it is doubted that any of them can pass under present circumstances. Even if departments of public work and social welfare should be established, Congress is not believed to be in a mood to delegate authority to the President over such important "arms" of government service as the comptroller general's office and Interstate Commerce, Federal Trade, Communications, and Power Commissions, or willing to relinquish control over the disposition of public works appropriations and authority. Feelings along these lines, in the Congress, are believed to be almost as deep seated as that involved in the present Supreme Court controversy.

Rural Electrification Administration

The Rural Electrification Administration had its second birthday on May 11, 1937. As of that date REA had approved 310 projects involving $58,952,958. Of that amount, about $56,862,958 will be used for line construction; $1,980,000 for building generating plants; and $110,000 for financing wiring and plumbing installation. Loan contracts have been executed for more than $45,500,000 of the allotted funds. Projects totaling about $32,000,000 have reached some one of the several stages of construction and according to REA enough wire has been strung on projects which it has financed to reach twice around the earth at the equator.

Some of the new REA procedures will be of interest to engineers in contact with rural electrification: Rural electric co-operatives are now required to use consulting engineering services. The co-operatives may also employ skilled management even before the lines are built and charge such salaries against REA loans until the project is completed and in operation. Help in building load is being supplied by REA experts working in the field under the direction of a small headquarters staff in Washington.

Engineers interested in the production and distribution of electric energy may also be interested in knowing that Administrator John C. Carmody of the Rural Electrification Administration has just announced that a new order of the Kentucky Public Service Commission establishes a whole-

sale rate of about 11 mills per kilowatt-hour, to be made available to rural co-operative projects by 7 private utility companies operating in Kentucky. In a telegram to Governor Chandler, Administrator Carmody states that the Kentucky action "might well serve as a model for other state commissions."

National Rivers and Harbors Congress

The outstanding feature of the April 1937 meeting of The National Rivers and Harbors Conference was the attention given to various features of water use and control in our river basins other than navigation. In past sessions of this congress, the emphasis has been placed upon navigation and water transportation. At this session, consideration was given to such factors as flood control, stream pollution, power development, water supply for municipal and industrial purposes, and biological and recreational uses.

After a series of addresses and discussions on each of these factors, the following resolution was unanimously adopted: "Ample funds should be provided at once to construct flood control projects already authorized by Congress—There should be no stint where human life and human misery are involved—Nothing substantial has been undertaken to prevent a recurrence of these catastrophies, largely through lack of appropriation—At this very moment another flood is generating at Johnstown, Pittsburgh, and the upper Ohio valley and still there is delay and lethargy."

Two diametrically opposite plans for water resources development received emphasis in this meeting. The first plan is exemplified by the Tennessee Valley Authority and the recent legislation proposed by Senators Barkley, Bulkley, and Norris providing for a series of similar projects throughout the country. The second plan contemplates the co-ordination of federal, state, and local agencies according to the recommendations of the National Resources Committee in the development of basin plans and programs for the various phases of water use and control including navigation, water power, municipal and industrial water supply, sanitation, irrigation, drainage, soil conservation, and the biological and recreational uses.

Council's present attitude favors the plan of co-ordination but the matter is before the AEC committee on the conservation and utilization of natural resources and its recommendation is yet to have consideration by the executive committee and the assembly. In the meantime Council shall be glad to have both opinions and suggestions from individual engineers and member engineering organizations on these questions of such vital social and economic implication.

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy, to be an inked drawing but without lettering, and other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

A Power Scale for the Instant Heavisidion

To the Editor:

At the AIEE winter convention in 1923 the writer demonstrated and described a computing kinematic device for long transmission lines which he named the "Heavisidion" ("The 'Heavisidion,' "AIEE TRANSACTIONS, volume 42, 1923, pages 42–53). With this device, the desired current and voltage having been set in their proper vectorial relationship at one end of the line, the corresponding quantities anywhere on the line, including the other end, could be obtained by a simple rotation of certain portions of the linkages. Moreover, the device was adjustable for any desired line constants and length of the line. Later, the author designed and built a simpler device, suitable only for a particular line and with the electrical quantities indicated only at the 2 ends of the line, but not at intermediate points ("The Instant Heavisidion," *General Electric Review*, volume 28, 1925, page 746). Both these devices indicate the current, the voltage, and the power factor, so that the power may be readily computed. However, it is convenient to have the real, reactive, and apparent power indicated directly on the device, in order to see at once their approximate magnitude and note the sense in which they vary as the load is varied. This is of particular importance in studies of static stability of a line, for which studies the device is particularly suited.

During the spring of 1937, a large heavisidion was built by 2 of the writer's students (figure 1) to illustrate the electrical relationships which may be expected on the 275-kv line between Boulder Dam and the city of Los Angeles. The device was quite carefully and accurately made out of steel bars and so proportioned that the electrical quantities could be scaled off from no load to short circuit within quite a wide range of operating voltages. The measured currents and voltages agreed with those analytically computed by means of hyperbolic functions of a complex variable to within better than one per cent. It was therefore deemed opportune to add a power scale to the device to enable true kilowatts, reactive kilovolt-amperes and apparent power to be read off directly.

The principle upon which the power scale is based is shown in figure 2. The line *CO* is the same as that in figure 2 in the article in the *General Electric Review*, referred to above. The line *CD* is drawn at an angle θ to it, θ being the same as in that article. *CB* is the current vector whose correct phase angle ϕ is with respect to *CD*, and not *CO*. *CDFG* is a piece of ruled paper (ordinary cross-section paper with decimal divisions will do). *HJ* is a guide, and *CK* is a straightedge whose lower side, *UMN*, passes through *C* and is used in measuring power. The straightedge can be fastened at any point of the guide by means of the thumbscrew at *L*. *S* and *T* are 2 markers which can slide along *CG* in grooves or along straight guides, to fix the values of the real and reactive power until the next reading. The kilovolt scale along the edge *FG* is a nonuniform scale, computed as is explained below. The setting at *U* must be the same as the value of the voltage *OC*. Thus, if *OC* is 300 kv, the straightedge must be set for the division 300 at *U*. If, however, *OC* is read in centimeters and not in kilovolts another scale along *FG* must be used, also calibrated in centimeters, but in reality a nonuniform scale.

The use of this attachment is as follows: Having set the Heavisidion for some desired currents and voltages, read *OC* (in centimeters or in kilovolts) and set the straightedge *CK* accordingly. Follow the ruled line *BN* to point *N* and set the marker *S*, following the ruled line *NS*. *CS* gives the real power, on the scale marked on *CG*, directly in kilowatts. With a pair of dividers transfer the reactive component of the current, *CR*, into the position *CR'*. Follow *R'M* with the eye, and set the marker *T* accordingly. *CT* will give the reactive kilovolt-amperes, to the same scale as the real power. If the total kilovolt-amperes

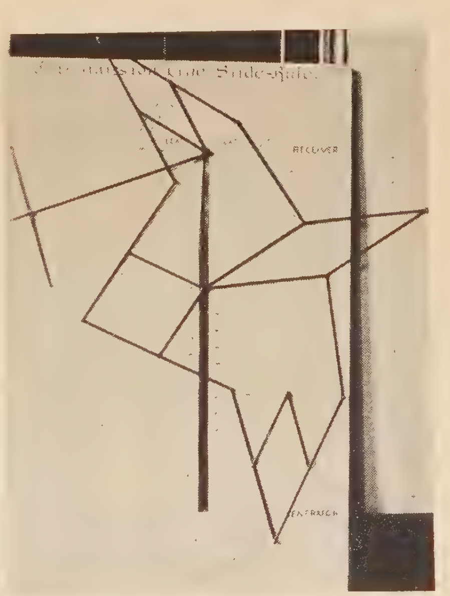


Figure 1

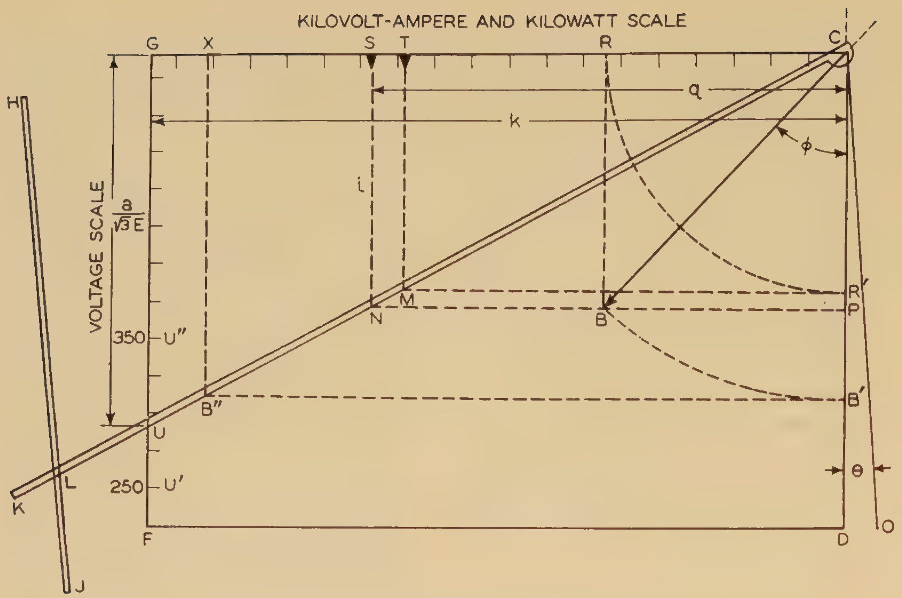


Figure 2

are desired, transfer B to B', follow $B'B''$ to its intersection with KC, and read CX on the kilowatt scale, as before.

The foregoing arrangement is based on the similarity of the triangles UGC and NSC. We have

$$UG/GC = NS/SC \tag{1}$$

Make $UG = a/(E\sqrt{3})$, where a is a convenient arbitrary constant, and E is the line voltage OC. GC is an arbitrary length denoted by k. NS is the power component, i, of the line current. SC must be the value of the real power, $iE\sqrt{3}$; let it be denoted by q. Equation 1 may therefore be rewritten in the following form:

$$a/(Ek\sqrt{3}) = i/q \tag{2}$$

from which

$$q = Eik\sqrt{3}/a \tag{3}$$

Since a and k are arbitrary constants, they can be so chosen that q will give the 3-phase power, $Ei\sqrt{3}$.

The following example illustrates the choice of the scales. Let the range of operating voltages be from 250 to 350 kv. Choose arbitrarily $a = 25 \times 35 \times \sqrt{3}$. For $E = 250$ kv, the length GU' will be 35 centimeters, but the division marked there will be 250 kv. For GU'' the length will be 25 centimeters, but the voltage marked there will be 350. Any number of intermediate divisions may be similarly computed, and a fairly detailed nonuniform scale drawn. Let the current scale be 1 centimeter = 50 amperes, and let us compute the conditions for an in-phase component $i = 400$ amperes, or 8 centimeters. Let the line voltage be 350 kv, so that the real power is 242,500 kw. To pick out a convenient value for $k = CG$, we reason as follows: NS is 8 centimeters, and GU is 25 centimeters (assuming U to be at 350 kv). Hence, the division of the power scale at G must be (25/8) 242,500 = 758,000 kw. It is therefore convenient to choose 1 centimeter = 20,000 kw, making the length CG = 37.9 centimeters. The same power scale will be correct, by construction, for any other value of the line voltage.

One could establish theoretical equations for the interdependence of the scales, but it seems that a few trials, such as the foregoing example, will readily permit to choose the most convenient proportions within the available space on the board. The power scale is shown in the upper left corner in figure 1. The board on which the Heavisidion is mounted is 42 by 64 inches; this will give the idea about the size of the device.

The writer wishes to express his appreciation of the help rendered by his 2 former students, Robert R. Gay (Enrolled Student) and Paul H. Hunter, both Cornell '37, who computed the sizes of the linkages and actually built and assembled the device following the writer's instructions in the 2 above-mentioned articles.

Very truly yours,

VLADIMIR KARAPETOFF
(A'03, F'12, Life Member)
Cornell University, Ithaca, N. Y.

Articles on Radio in "Electrical Engineering"

To the Editor:

This is just a note to let you know how attractive the June issue of ELECTRICAL ENGINEERING is with its cover lettered in red. I am sure that the combination of color printing and the unique paper which is used makes this publication by all odds the most pleasing in appearance of the 20-odd periodicals which reach my desk every month.

I will also take this opportunity to tell you how pleased I was to find not just one but 2 articles on radio in the June issue. When it is remembered that the radio industry produced about 8-million receivers last year, the importance of this branch of electrical engineering stands out. I trust that this field will continue to receive the attention it so clearly deserves in ELECTRICAL ENGINEERING.

Very truly yours,

ALBERT R. HODGES (A'37)
Associate, Ralph H. Langley,
Consulting Engineer
165 Broadway, New York, N. Y.

Induction Motors on Unbalanced Voltages

To the Editor:

I wish to point out some errors in my discussion which appeared in the May 1937 issue of ELECTRICAL ENGINEERING on page 621.

In the center column the equation appears,

$$I_c = I$$

This should be

$$I_c = -I$$

Lower down in the same column the equation

$$V_{bc} = j(\sqrt{3}\, V_{s1} - V_{s2})$$

is shown. This should be

$$V_{bc} = j\sqrt{3}\,(V_{s1} - V_{s2})$$

Equation 1 reads

$$I_{s1} = I_{s2}$$

This should be

$$I_{s1} = -I_{s2}$$

The second line of equation 4 appears as,

$$V_b = \alpha^2 I_1 Z_1 + \alpha I_2 V_2 - (I_1 + I_2)\,Z_0$$

This should be,

$$V_b = \alpha^2 I_1 Z_1 + \alpha I_2 Z_2 - (I_1 + I_2)\,Z_0$$

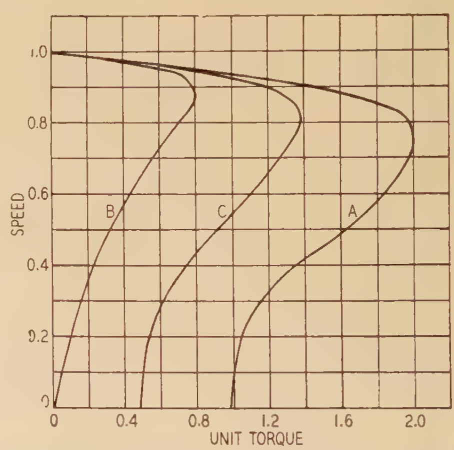


Figure 4. Speed-torque characteristics of a 5-horsepower 220-volt 3-phase 60-cycle 6-pole induction motor

A—Normal 3-phase operation
B—Single-phase operation, line-to-line voltage
C—Operation on 2 of the 3 phases
The motor constants in unit values are as follows:

r_{s1} = 0.044
r_{r1} = 0.067
Z_0 = 0.044 + j 0.140
Y_{m1} = 0.023 + j 0.380
X_{s1} + 0.140
X_{r1} = 0.140

The speed-torque curves of figure 4 were not published in the May issue and are therefore given here.

Very truly yours,

H. J. REEVES (A'30)
PAUL AND REEVES,
Spokane, Wash.

Personal Items

B. J. Arnold (A'92, F'12, past-president, member for life) consulting engineer, Chicago, Ill., has been elected an Honorary Member of the Institute. Colonel Arnold was born at Casnovia, Mich., in 1861, and received the degrees of bachelor of science (1884) and mechanical engineer (1887) at Hillsdale College; later, he took a graduate course in electrical engineering at Cornell University, in 1897 received the degree of electrical engineer from the University of Nebraska, and at various times has received several honorary degrees. One of Colonel Arnold's first important engineering projects was the design and construction of the Intramural Elevated Railway at the Columbian Exposition in Chicago, in 1893. This was the first commercial demonstration of the third rail on a large scale. Later he did pioneer work of construction for such railroads as the Chicago-Milwaukee Electric Railway and the Lansing, St. Johns, and St. Louis Railway in Michigan. For the latter company he devised, in 1900, a single-phase a-c system. Colonel Arnold electrified the Grand Trunk Railroad through the St. Clair Tunnel from Port Huron, Mich., to Sarnia, Ont., Canada, and used for the first time a single-phase high-voltage system for heavy electric railway work. Among his other important commissions were the electrification of the Grand Central Terminal, New York, N. Y., and the development of the subway system in New York. He has been a consultant on surface and underground traction problems for cities throughout the United States and consulting engineer for numerous railroad commissions. During the World War Colonel Arnold served in various capacities, being assigned as lieutenant colonel in the aviation section in 1917, to make a complete survey of aircraft supply and production facilities for the United States Army and Navy, and to take charge of the development and production of aerial torpedos. He has served the Institute as manager, 1895–98; vice-president, 1902–03; and president, 1903–04. In addition, he has served as a member of the committees on education, 1924–26; meetings and papers (now technical program), 1902–03 and 1908–09; executive, 1924–26. He was a member of the American Committee on Electrolysis (1914–21 and 1922–32) and of the John Fritz Medal board of award during 1905–08. Colonel Arnold received the Washington Award of the Western Society of Engineers in 1929, and is a member of many technical and engineering societies, including the American Society of Civil Engineers, The American Society of Mechanical Engineers, and the American Society for the Promotion of Engineering Education.

P. S. Millar (A'03, M'13) president, Electrical Testing Laboratories, Inc., New York, N. Y., has received the 1936 AIEE national prize award for best paper in engineering practice for his paper "The Qualities of Incandescent Lamps." Mr. Millar was born at Andover, N. J., in 1880, and obtained his formal technical education at Paterson Classical and Scientific School and through the International Correspondence Schools. In 1897 he entered the employ of the Lamp Testing Bureau (now Electrical Testing Laboratories, Inc.) and in 1899 became assistant manager of that organization. He became general manager in 1914, and has been president since 1930. Mr. Millar has done much original work in illumination research, being co-inventor of the Sharp-Millar photometer, and has contributed liberally to the technical press. He has been a member of the Institute's committees on electrophysics, 1917–18; meetings and papers (now technical program), 1925–28; and production and application of light (chairman, 1925–28) since 1924. Recently he was elected president of the United States National Committee of the International Commission on Illumination. Mr. Millar is a fellow of the American Physical Society, member of the council of the Association of Consulting Chemists and Chemical Engineers, secretary-treasurer of the Association of Edison Electric Illuminating Companies, member and past-president of the Illuminating Engineering Society, and a director of the Thomas Alva Edison Foundation.

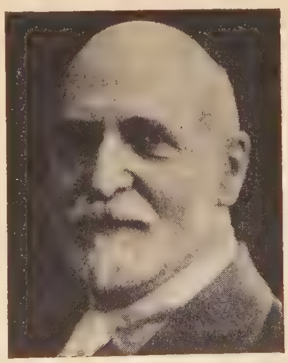
Alex Dow (A'93, F'13, member for life) president, Detroit (Mich.) Edison Company has been elected an Honorary Member, the highest grade of membership in the Institute. The petition proposing his election as Honorary Member stated: "Doctor Dow's responsible guidance has developed one of the great utility companies, which has, throughout this long period [Doctor Dow has been President of the Detroit Edison Company for 24 years] been in the van of technical progress and which has maintained a high standard of service in the public interest." He has been a leading pioneer in the United States in the engineering, rate making, and general operation of the electric light and power utility, and is given credit for both the engineering and financial success of his enterprises. He is considered the father of the so-called "big" steam boiler in the United States and was the first to adopt the underfeed stoker for large installations. A more complete biographical sketch of Doctor Dow was published in the January 1937 issue of Electrical Engineering (page 197) upon the occasion of the award to him of the AIEE Edison Medal for 1936 "for outstanding leadership in the development of the central station industry and its service to the public."

W. J. Lyman (A'25) electrical planning engineer, Duquesne Light Company, Pittsburgh, Pa., has received honorable mention in the 1936 AIEE national prize awards for best paper in engineering practice for his paper "The Relation Between Load, Capacity, and Service Continuity on an Electric Power System." Mr. Lyman was born August 30, 1901, at Cambridge, Mass., and received the degree of bachelor of science in electrical engineering at Carnegie Institute of Technology in 1924. Prior to his enrollment at that school he was affiliated briefly with the Turners Falls Power and Electric Company, Greenfield, Mass., and the Automatic Transportation Company, Buffalo, N. Y. In 1924 he entered the employ of the Duquesne Light Company as an apprentice engineer, but in the following year was transferred to the planning division of that company, where his work has consisted of engineering and economy planning for the entire system. Mr. Lyman has been electrical planning engineer since 1929, in which capacity he has been in entire charge of the electrical planning section. From 1927 to 1932 he served as a member of the lightning arrester subcommittee of the AIEE protective devices committee, and was active in committee work of the former National Electric Light Association. In addition to his regular duties, Mr. Lyman has taught technical subjects in the night school at Carnegie Institute of Technology since 1924. He has written several technical papers and articles, including 2 papers presented before the Institute.

H. P. Seelye (A'19, M'28) engineer for The Detroit (Mich.) Edison Company, has received honorable mention in the 1936 AIEE national prize awards for best paper in engineering practice for his paper "Modernization of Power Distribution Systems." Mr. Seelye was born June 27, 1890, and was graduated from the University of Michigan

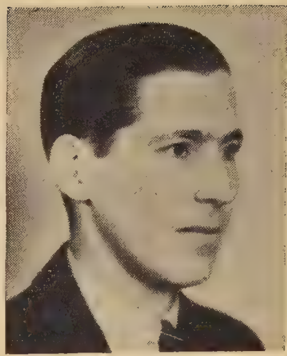
P. S. MILLAR

B. J. ARNOLD

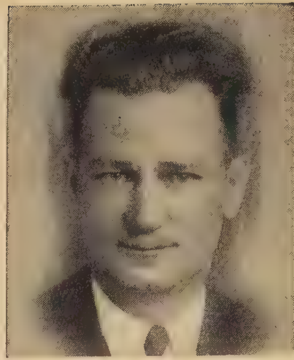


ALEX DOW

with a degree in civil engineering in 1912. After 4 years of varied engineering training, he entered the employ of The Detroit Edison Company in 1916, and since that time has been engaged in transmission and distribution engineering problems and design. Mr. Seelye now is in active charge of the transmission and distribution section of the Company. He was chairman of the AIEE Detroit-Ann Arbor Section during 1935–36, and is a member of the distribution subcommittee of the AIEE committee on power transmission and distribution and the electrical standards committee of the American Standards Association. In addition, he is a sponsor of the group on standards and specifications of the transmission and distribution committee of the Edison Electric Institute. Mr. Seelye is the author of 2 books: "Electrical Distribution Engineering" and "Economics of Electrical Distribution."



D. H. ROWLAND



H. R. WOODROW

H. E. EDGERTON

H. R. Woodrow (A'12, F'23) vice-president, Brooklyn (N. Y.) Edison Company, Inc., has been elected vice-president of the Consolidated Edison Company of New York, Inc., New York, N. Y. Mr. Woodrow was born April 15, 1887, at Luverne, Minn., and received the degrees of bachelor of science (1909) and master of science (1911) at Drake University and University of Illinois, respectively. Following his graduation in 1911 he joined the engineering staff of The New York Edison Company, Inc., as assistant to the chief electrical engineer, and held that position until he was appointed assistant chief electrical engineer in 1917. In 1920 he became affiliated with Stone and Webster, Inc., as an electrical engineer, but remained with that company for only one year before transferring to the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., as a general engineer. Mr. Woodrow entered the employ of the Brooklyn Edison Company in 1922 as an assistant electrical engineer. Four years later he was promoted to electrical engineer, and since 1932 he has been vice-president. He served the Institute as a director from 1931 to 1935, and is at present serving as its representative to the United Engineering Trustees for the term 1934–37, just ending. He has also served as a member of many of the Institute's technical committees.

H. E. Edgerton (A'27, M'32) assistant professor of electrical engineering, Massachusetts Institute of Technology, Cambridge, has received the 1936 AIEE national prize award for best paper in theory and research for his paper "High Speed Motion Pictures." Doctor Edgerton was born April 6, 1906, at Fremont, Nebr., and was graduated in electrical engineering from the University of Nebraska in 1925, following which he entered the test course of the General Electric Company, Schenectady, N. Y. In 1926 he enrolled in the graduate school of Massachusetts Institute of Technology and received from that institution the degrees of master of science (1927) and doctor of science (1931). During 1927–28 Doctor Edgerton served as a research assistant, and in the following year was appointed to the faculty of MIT as an instructor in electrical engineering. He became assistant professor in 1932. His graduate work for his doctor's degree consisted of research on synchronous machines and stroboscopes, and much of his subsequent research has been of a similar nature. He has become widely recognized for his accomplishments in studying motions of machines and moving parts by means of high-speed motion pictures. Doctor Edgerton served as a member of the Institute's committee on electrical machinery from 1931 to 1935.

D. H. Rowland (A'26) research engineer, Locke Insulator Corporation, Baltimore, Md., has received the 1936 AIEE national prize award for initial paper for his paper "Porcelain for High Voltage Insulators." Mr. Rowland was born December 25, 1898, at Baltimore, and received the degree of bachelor of science in electrical engineering at The Johns Hopkins University in 1922; however, his college training was interrupted by his service in the United States Army during the World War, and at the conclusion of the war Mr. Rowland went to Paris, France, to study physics and mathematics at the Sorbonne University before returning to the United States. Following his graduation he was employed in the statistical department of Stone and Webster, Boston, Mass., but shortly thereafter he entered the lightning protection department of the Western Union Company, New York, N. Y. In 1922 Mr. Rowland became affiliated with the Locke Insulator Corporation and in various capacities has since served that company continuously. He is the author of several technical articles on ceramics as related to insulators. He is a member of Tau Beta Pi and Omega Delta Kappa honorary fraternities.

W. L. Smith (M'22) professor and head of the department of electrical engineering, Northeastern University, Boston, Mass., recently retired from active duty, after more than 40 years of service. Professor Smith was born September 6, 1867, at Concord, Mass., and was graduated in electrical engineering from Massachusetts Institute of Technology in 1890. Following his graduation he was appointed to the faculty of the same institution as an assistant in physics; later, he became an assistant in electrical engineering and an instructor in electrical engineering, but resigned in 1902 to pursue experimental and consulting-engineering work. Professor Smith has been head of the department of electrical engineering since the incorporation of Northeastern University in 1916.

A. A. Low (M'37) executive vice-president, Brooklyn (N. Y.) Edison Company, Inc., has been elected vice-president of the Consolidated Edison Company of New York, Inc., New York, N. Y. Mr. Low was born August 1, 1889, at Saratoga Springs, N. Y., and received the degree of bachelor of arts at Yale University in 1911. He entered the public utility field in 1928 as organizer and president of the Old Forge (N. Y.) Electric Company. In 1931 he became affiliated with the Utica (N. Y.) Gas and Electric Company as executive vice-president, which position he held for 3 years before being elected president of that company in 1934. Mr. Low became identified with the Brooklyn Edison Company in 1936 as executive vice-president in responsible charge of operations.

W. R. Harry (A'37) Bell Telephone Laboratories, Incorporated, New York, N. Y. has received honorable mention in the 1936 AIEE national prize awards for Branch paper for his paper "A High-Speed Vibration Analyzer." Mr. Harry is a native (1912) of Detroit, Mich., and an electrical engineering graduate of Cornell University. Prior to graduation, he was employed during summer vacations by The Detroit Edison Company and radio station CKLW, Windsor, Ont., Canada. Since the beginning of his association with the Bell Telephone Laboratories, in 1936, he has been engaged in the derivation of a new microphone for broadcast use.

W. P. Graham (A'02, F'23) acting chancellor, Syracuse University, Syracuse, N. Y., has been appointed chancellor. As stated in a biographical sketch of Doctor Graham published in the December 1936 issue of Electrical Engineering (page 1404) he has been affiliated with the university for almost 40 years, and was vice-chancellor for 15 years prior to his appointment as acting chancellor in 1936.

W. J. Walsh (Enrolled Student) graduate student in electrical engineering at Oregon State College, Corvallis, has been awarded the 1936 AIEE national prize award for

Branch paper for his paper "Heat Transfer Efficiency of Electric Range Surface Units." Mr. Walsh was born February 7, 1915, at Portland, Me., and received the degree of bachelor of science in electrical engineering at Oregon State College in 1936. In addition to his regular scholastic work, Mr. Walsh serves as a research assistant in the Oregon State College Engineering Experiment Station. He is a member of Tau Beta Pi, Eta Kappa Nu, Phi Kappa Phi, and Sigma Xi.

G. H. JONES (A'02, F'12) for many years power engineer for the Commonwealth Edison Company, Chicago, Ill., recently was appointed manager of power sales. Mr. Jones was born at Fond du Lac, Wis., in 1874, and received the degree of bachelor of science in electrical engineering at the University of Wisconsin in 1897. He became affiliated with the Commonwealth Edison Company in 1909.

E. S. SIEVERS (A'34) who has been a sales engineer in the New York (N. Y.) offices of the Weston Electrical Instrument Corporation, has been transferred to Los Angeles, Calif., as assistant to the Weston company's representative in that area. Mr. Sievers has been associated with the Weston organization continuously since his graduation from Purdue University in 1934.

T. H. HAINES (A'23, M'31) superintendent, distribution department, Edison Electric Illuminating Company of Boston, Mass., has been appointed a representative of the AIEE on the Sectional Committee on National Electrical Safety Code.

W. C. GOODWIN (M'33) air conditioning department, Westinghouse Electric & Manufacturing Company, Mansfield, Ohio, has been appointed a representative of the AIEE on the Sectional Committee of Safety Code for Mechanical Refrigeration.

H. B. GEAR (A'01, F'20, director) vice president in charge of operating and engineering, Commonwealth Edison Company, Chicago, Ill., has been appointed a representative of the AIEE on the Commission of Washington Award for the 2-year term beginning August 1, 1937.

J. F. LAMBIAS, JR. (A'36) formerly a distribution draftsman for the Brooklyn (N. Y.) Edison Company, now is a junior engineer in the evaluation bureau of the New York and Queens Electric Light and Power Company, Long Island City, N. Y.

S. P. SAWYER (A'30) formerly assistant district engineer, New England Power Service Corporation, Northampton, Mass., now is assistant superintendent of distribution, Central Massachusetts Electric Company, Palmer, Mass.

L. L. ROBINSON (A'31) who has been employed by the Kinnear Manufacturing Company, Columbus, Ohio, now is associated with the production division of the Marion Steam Shovel Company, Marion, Ohio.

S. A. SMITH, JR. (A'24, M'31) resigned recently from the Public Service Electric and Gas Company, Newark, N. J., to become affiliated with the engineering department of the General Cable Corporation, New York, N. Y.

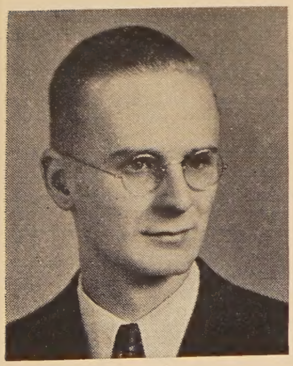
F. W. MEYEREND (A'34) electrical engineer, John A. Roebling's Sons Company, San Francisco, Calif., has been transferred to the Trenton, N. J., offices of that Company.

FRANK MANSUR (A'35) local agent for the Southern California Edison Company, Placentia, Calif., has been appointed commercial and industrial lighting specialist for that company, with offices at Santa Ana.

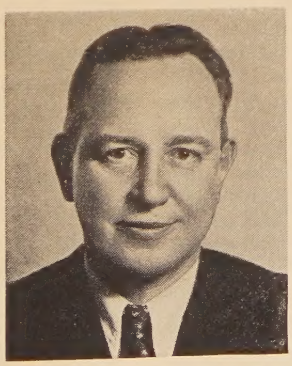
M. M. DE LASCURAIN (A'36) recently resigned his position in the engineering department of the General Electric Company, Mexico City, Mexico, to become sales manager of Cía Comercial Ericsson, Mexico City.

K. C. HOLLISTER (A'35) assistant sales engineer, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., has been transferred to the New York (N. Y.) offices of that company.

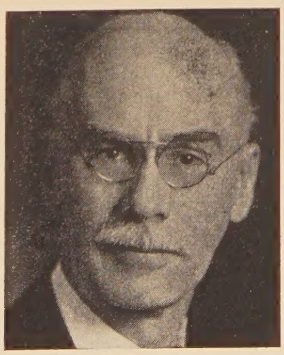
JOSEPH GLADIS (A'27) who has been employed by the Board of Transportation, City of New York, N. Y., now is affiliated with the switchgear engineering department of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.



W. J. WALSH



A. A. LOW



W. P. GRAHAM

C. H. ANDERSON (M'34) formerly general superintendent of the Ontario division of the Niagara, Lockport, and Ontario Power Company, Medina, N. Y., now is general superintendent of the Niagara Falls division of the Buffalo and Niagara Electric Corporation, Niagara Falls, N. Y.

NATHAN FRIEDLAND (A'36) formerly production manager of Belmet Products, Inc., Brooklyn, N. Y., now is employed in the office of the signal engineer of the Interborough Rapid Transit Company, New York, N. Y.

W. C. STEWART (A'28) formerly an engineer in the data division of the General Electric Company, Schenectady, N. Y. has become technical adviser to the American Institute of Bolt, Nut, and Rivet Manufacturers, Cleveland, Ohio.

PAUL SHAAD (A'34) student engineer, General Electric Company, Schenectady, N. Y., has been transferred to the San Francisco, Calif., offices of that company.

H. W. GIESECKE (A'35) formerly employed in the electrical department of the Federal Shipbuilding & Dry Dock Company, New York, N. Y., now is an engineer in the general engineering department of the Standard Oil Development Company, Elizabeth, N. J.

B. V. HOARD (M'36) who has been an engineering assistant in the plant bureau of the Consolidated Edison Company of New York, Inc., New York, N. Y., now is with the Westinghouse Electric & Manufacturing Company, Newark, N. J.

TALIAFERRO MILTON (A'11, F'20) has been appointed special representative of the K. W. Battery Company, with headquarters at Chicago, Ill.

Obituary

AMBROSE SWASEY (HM'28) chairman of the board, The Warner and Swasey Company, Cleveland, Ohio, died at his summer home in Exeter, N. H., June 15, 1937, in his 91st year. Doctor Swasey was born at Exeter, N. H., December 19, 1846. During the period 1869–80 he was with the Pratt and Whitney Company, Hartford, Conn., where he gave special attention to problems of gearing. In 1880 he formed a partnership with W. R. Warner, the firm being incorporated in 1900 as The Warner and Swasey Company. The company engaged in the manufacture of machine tools and astronomical instruments at Chicago, Ill., moving later to Cleveland, Ohio. Doctor Swasey has been chairman of the board since the death of Mr. Warner. In 1914, he established the Engineering Foundation, research agency of the 4 national societies of civil, mining and metallurgical, mechanical, and electrical engineers. He has contributed gifts totaling more than $750,000 to the Foundation. Doctor Swasey's many

honors include: The John Fritz Gold Medal, 1924; Franklin Medal, highest award of the Franklin Institute; Washington Award, 1935; The Second Hoover Gold Medal, 1936; and the Medal of Honor of the Verein Deutscher Ingenieure, 1936. In addition to honorary membership in the AIEE, which was awarded him June 27, 1928, he is an honorary member of The American Society of Mechanical Engineers (president 1904), American Society of Civil Engineers, Institution of Mechanical Engineers (Great Britain), Institution of Mining Engineers (Great Britain), and the Society of Civil Engineers. He is a chevalier and officer of the French Legion of Honor, and has received several honorary degrees in the United States.

Arthur Langley Mudge (A'01, M'12, F'12) consulting electrical engineer, Toronto, Ont., Canada, died April 29, 1937. Mr. Mudge was born October 17, 1873, at Montreal, Que., Canada, and was graduated in mechanical engineering at McGill University in 1894; in 1895 he received a degree in electrical engineering at the same institution and almost at once joined the Canadian General Electric Company, Peterborough, Ont., as an instructor in the student training course. In 1897 Mr. Mudge became affiliated with the Royal Electric Company, Montreal, where he remained for 2 years as a test engineer before being appointed electrical engineer for the Grand Trunk Railway Company. In 1901 Mr. Mudge became engaged as a test engineer for the Stanley Electric Manufacturing Company, Pittsfield, Mass., but in 1904 he began a series of brief associations with the Allis-Chalmers Manufacturing Company in the United States and the Allis-Chalmers-Bullock Company and the Crocker-Wheeler Company, Ltd., in Canada, which lasted until 1908. At that time he joined the consulting engineering firm of Smith, Kerry, and Chace, Toronto, and was placed in charge of the electrical department. He remained with that company until 1925, when he was appointed senior electrical engineer with the joint board of engineers in the Canadian section of the St. Lawrence waterways project. In 1927 Mr. Mudge was appointed senior electrical engineer of the Welland Ship Canal and remained in charge until construction was completed. He was chairman of the AIEE Toronto Section during 1911–12, was a past-vice-president of the Canadian Electrical Association, and a member of the Association of Professional Engineers of Ontario.

Harry Milton Dearmin (A'22, M'28) supervising draftsman, Pacific Gas and Electric Company, San Francisco, Calif., died recently. Mr. Dearmin was born September 16, 1895, at Hillsboro, Texas, and received the degree of associate in electrical engineering at the Polytechnic College of Engineering. Following brief periods of association with the Pacific Gas and Electric Company, the Marconi Wireless Telegraph Company of America, and the Western Electric Company, he entered the employ of the United Electric Vehicle Company, Oakland, Calif., and was placed in charge of plant maintenance. He was affiliated with that company for only one year, however, before enlisting in the United States Navy, in 1917, as an electrician. Later he was promoted to the rank of ensign, and was made an inspector of machinery at the Union Iron Works, San Francisco. At the end of the World War Mr. Dearmin joined the engineering staff of the Pacific Gas and Electric Company as a designer, and had been a supervising draftsman since 1924.

Elden S. Code (A'11, M'20) electrical engineer, Westinghouse Electric & Manufacturing Company, Seattle, Wash,. died January 1, 1937, according to word just received at Institute headquarters. Mr. Code was born January 15, 1883, at Carleton Place, Ont., Canada, and received the degree of bachelor of science in electrical engineering at Queens University in 1907. Following his graduation, he entered the electrical engineering apprenticeship course of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa., and upon completion of the course was transferred to the switchboard engineering department of that company. In 1910 he was sent to the Seattle offices of the Westinghouse company. His work there comprised sales and design work for industrial, power, railway, and lighting projects, and his service extended over more than 25 years.

Michael Romano (A'20) manager and treasurer, Hackett Products Company, Inc., Providence, R. I., died March 21, 1937. Mr. Romano was born in Italy, February 15, 1886, and attended Lowell Institute and Massachusetts Institute of Technology. From 1908 to 1914 he served the General Fire Extinguisher Company, Providence, first as an electrician and later as maintenance engineer. In 1914 he entered the employ of the General Electric Company, Schenectady, N. Y., as a test engineer and remained there for 4 years before becoming an inspector for the United States Navy. He became associated with the Hackett Products Company, Inc., in 1925.

Zella A. McBerty (A'24) secretary and treasurer of The Federal Machine and Welder Company, Warren, Ohio, and one of the few women members of the Institute, died May 24, 1937. Mrs. McBerty was born August 27, 1878, at Mineral Ridge, Ohio, and received her formal technical training through private instruction. In 1913 she became interested in electric welding, and began to design low-voltage transformers and electric welding machines. In the following year she became affiliated with the National Electric Welder Company, Warren, and her service with that company and its successor, The Federal Machine and Welder Company, was continuous for more than 22 years. Mrs. McBerty had retired from active service on the day of her death.

Emil M. Kaegi (M'36) electrical engineer for the Allis-Chalmers Manufacturing Company, Milwaukee, Wis., died recently. Mr. Kaegi was born June 21, 1900, at Zurich, Switzerland, and received his technical education by serving an apprenticeship with the Trueb Tauber Company, Zurich, from 1915 to 1919. In 1919 he became a designer of d-c control apparatus for the Brown Boveri Company, at Baden, Switzerland, but in the following year came to the United States, where he secured a position with the Hoskins Manufacturing Company, Detroit, Mich., and remained 2 years. After a brief association with the F. B. Electrical Company and the Premier Radio Corporation, Detroit, Mich., he joined the Brown Boveri Company, Camden, N. J., and was placed in charge of the drafting department for rectifiers and auxiliary equipment. In that capacity Mr. Kaegi supervised the design of several large substations in the United States and Canada, and when the Brown Boveri Company was purchased by the Allis-Chalmers Manufacturing Company in 1931, he was retained in the same position, but with the title of electrical engineer.

Thomas Hoskins Kettig (A'34) construction superintendent, Southern Bell Telephone and Telegraph Company, Louisville, Ky., died February 12, 1937. Mr. Kettig was born at Louisville, August 2, 1889, and received his education in the public schools there. He served the Southern Bell Telephone and Telegraph Company in various capacities for 31 years, and was superintendent of construction in the Kentucky division for more than 12 years.

Membership

Recommended for Transfer

The board of examiners, at its meeting on June 16, 1937, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Bailey, R. Cooper, system control engineer, Virginia Electric and Power Company, Richmond.
Spurck, R. M., manager, circuit breaker sales, General Electric Company, Philadelphia, Pa.
2 to Grade of Fellow

To Grade of Member

Blevins, Edward, assistant superintendent, Tampa Electric Company, Plant City, Fla.
Burroway, A. C., division plant superintendent, Cincinnati and Suburban Bell Telephone Company, Cincinnati, Ohio.
Carlin, P. J., superintendent of distribution, Florida Power and Light Company, Miami.
Concordia, C., engineer, General Electric Company, Schenectady, N. Y.
Coursey, R. W., underground engineer, Oklahoma Gas and Electric Company, Oklahoma City.
Crary, S. B., member central station department, General Electric Company, Schenectady, N. Y.
Dean, C. E., radio engineer, Hazeltine Service Corporation, New York, N. Y.
Fife, S. T., professor of electrical engineering, and head of department, University of Louisville, Louisville, Ky.
Holton, J. L., assistant distribution engineer, New York and Queens Electric Light and Power Company, Flushing, N. Y.
Houchens, J. M., co-ordinator (assistant professor), University of Louisville, Louisville, Ky.
Howes, J. C., electrical engineer, General Electric Company, Pittsfield, Mass.
Jones, J. Coleman, superintendent of transmission, Florida Power and Light Company, Fort Pierce.
Lea, R. A., distribution engineer, Union Electric Light and Power Company, St. Louis, Mo.
Loeffler, B. T., division equipment engineer, Indiana Bell Telephone Company, Indianapolis, Ind.
Macalpine, William W., communication engineer, Federal Telegraph Company, Newark, N. J.
McMorris, William A., electrical engineer, General Electric Company, Pittsfield, Mass.

Miller, C. W., sales engineer, Westinghouse Electric & Manufacturing Company, New York, N. Y.
Mulligan, J. F., superintendent, transmission division, Consolidated Edison Company of New York, Inc., New York, N. Y.
Parker, William W., technician, switchgear engineering department, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Skone, R. C., resident engineer, Diablo Project, Rockport, Wash.
Southworth, H., assistant manager, Lawrence Gas and Electric Company, Lawrence, Mass.
Tadlock, W. L., supervising engineer, Commonwealth and Southern Corporation, Birmingham, Ala.
Town, G. R., research engineer, Stromberg-Carlson Telephone Manufacturing Company, Rochester, N. Y.

23 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before July 31, 1937, or Sept. 30, 1937, if the applicant resides outside of the United States or Canada.

Ashbaugh, E. G., Westinghouse Electric & Manufacturing Company, Sharon, Pa.
Byers, J. F., Libbey-Owens-Ford Glass Company, Charleston, W. Va.
Caldwell, C. A., Houston Lighting and Power Company, Houston, Texas.
Carter, R. C., Jr., Company 1843, Camp *NP-5-C*, Mesa Verde, Colo.
Coates, R. E., General Electric Company, Pittsfield, Mass.
Cooley, M. C. (Member), W. N. Matthews Corporation, St. Louis, Mo.
Corves, G. S., Southern New England Telephone Company, West Haven, Conn.
Dimmitt, E. H., Federal Power Commission, Washington, D. C.
Elmer, E. R., Jr., Underwriters' Laboratories, Inc., Chicago, Ill.
Fetherolf, J. M., in care of Edward J. Cheney, New York, N. Y.
Fox, C. E. (Member), 806 North Fifth Avenue, Knoxville, Tenn.
Goodburn, R. A., Florida Power and Light Company, Miami.
Harmon, L. B., Westinghouse Electric & Manufacturing Company, Los Angeles, Calif.
Hubbard, R. R., J. A. Adams Company, Indianapolis, Ind.
Jabour, E., Department of Light, Los Angeles, Calif.
Kearns, J. J., Crucible Steel Company of America, Harrison, N. J.
Kimball, A. L. (Member), Otis Elevator Company, Buffalo, N. Y.
Klumb, R. K., Southern California Edison Company, Ltd., Chino, Calif.
Lickey, H. F., State College of Washington, Pullman.
Madsen, R. V., Southern Pacific Golden Gate Ferries, San Francisco, Calif.
Mathes, R. E., RCA Communications, Inc., New York, N. Y.
McCormick, F. J. (Member), Wisconsin Telephone Company, Milwaukee, Wis.
Mellor, A. G., Buffalo, Niagara and Eastern Power Company, Buffalo, N. Y.
Miller, M. I., Carolina Power and Light Company, Raleigh, N. C.
O'Neal, F. C., Jr., Texas Electric Service Company, Eastland, Texas.
Parsons, C. W., Johnson Electric Supply Company, Cincinnati, Ohio.
Power, R. B., Jr., Kennecott Wire and Cable Company, Phillipsdale, R. I.
Ramsay, H. B., New Orleans Public Service, Inc., New Orleans, La.
Rogers, H., Jr., Western Electric Company, San Francisco, Calif.
Rossrucker, E. A., Ohio Bell Telephone Company, Cleveland, Ohio.
Scheer, G. B., San Francisco-Oakland Bay Bridge, San Francisco, Calif.
Selman, M. H., housing division, Public Works Administration, Washington, D. C.
Shannon, S. R., Jr., General Electric Company, Erie, Pa.
Sheblak, V. B., Bureau of Power and Light, Los Angeles, Calif.
Simmons, E. E., Jr., California Institute of Technology, Pasadena.
Sinnott, J. F., San Diego Consolidated Gas and Electric Company, San Diego, Calif.
Smith, C. J., Charles H. Smith and Company, Engineers, Inc., New York, N. Y.
Soares, Glen J., 5482 Kales Avenue, Oakland, Calif.
Stafford, D. E., National Electric Coil Company, Columbus, Ohio
Stahler, L. L., Florida Power and Light Company, Miami.
Taylor, W. F. (Member), New England Allis-Chalmers Manufacturing Company, Boston, Mass.
Tellez, J. S., Pipe Trades Service Company, Toledo, Ohio.
Thomson, W. T., 1224 Park Avenue, Alameda, Calif.
Vesely, S. M., Chicago Electric Company, Chicago, Ill.
Waidhas, G., Allis-Chalmers Manufacturing Company, West Allis, Wis.
Ward, S. J., Houston Light and Power Company, Houston, Texas.
White, E. L. (Member), Federal Communications Commission, Washington, D. C.
Willis, J. D., Canadian General Electric Company, Ltd., Toronto, Ont., Canada.
Witzke, R. L., Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.
Woolley, H. P., Woolley Welding and Machine, Houston, Texas.

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Foreign

Apte, S. V. (Member), College of Engineering, Poona, India.
Geltz, F., South American Development Company, Guayaquil, Ecuador.
Gordon, F., Cerro de Pasco Copper Corporation, La Oroya, Peru.
Madahar, G. D., Modern Electric Works, Lahore, Punjab, India.
Page, F. W., British Electrical and Allied Industries Research Association, London, England.
Shivapuri, P. R. N., Punjab Electric Power Company, Ltd., Gujrat, Punjab, India.

6 Foreign

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

CONTRIBUTIONS from the PHYSICAL LABORATORIES of HARVARD UNIVERSITY for the Years 1933, 1934, and 1935. Series II, 2 volumes. Cambridge, Mass., Harvard University Press, 1936–1937. Illustrated, 11x8 inches, volume 1, 628 pages; volume 2, 469 pages, leather, $2.50 each. Collections of 65 and 57 papers, respectively, on work done in the physics laboratories of Harvard University.

First Course in STATISTICAL METHOD. By G. I. Gavett. 2 edition. New York and London, McGraw-Hill Book Company, 1937. 400 pages, illustrated, 9x6 inches, cloth, $3.50. A textbook for use as a foundation course in "statistical method" for all fields in which the mathematical representation of facts is desirable.

ZERO to EIGHTY, being My Lifetime Doings, Reflections and Inventions, also My Journey around the Moon. By E. F. Northrup. Princeton, N. J., Scientific Publishing Company, 1937. 280 pages, illustrated, 10x6 inches, cloth, $3.00; foreign countries $3.50. Devoted to a presentation of the possibilities in the production of high linear velocities by the use of traveling waves of electric force. Cast in the form of the autobiography of a scientist living from 1920 to 2000 A.D.

(The) WORLD of ATOMS. By A. Haas. 2 edition, translated by G. B. Welch and H. S. Uhler. New York, D. Van Nostrand Company, 1937. 183 pages, illustrated, 9x6 inches, cloth, $3.00. A translation of the revision of a series of lectures intended to present to a lay public the achievements of modern atomic physics in as brief and yet thorough a manner as possible.

VALUATION of PROPERTY. 2 volumes. By J. C. Bonbright. New York and London, McGraw-Hill Book Company, 1937. 1271 pages, 9x6 inches cloth, $12.00. A presentation of the results of a research in legal and economic theories of property valuation. Volume 1 covers concepts of value, methods of valuation, and valuation for specific legal purposes. Volume 2 covers specific cases of valuation under certain rules, tax restrictions, and other legal considerations.

TECHNIQUE of MARKETING RESEARCH. Prepared by the Committee on Marketing Research Technique of the American Marketing Society. New York, McGraw-Hill Book Company, 1937. 432 pages, illustrated, 9x6 inches, cloth, $4.00. A review of methods for investigating problems in marketing policies, salability of products, markets, and selling.

SAE HANDBOOK, 1937 edition. New York, Society of Automotive Engineers. 774 pages, illustrated, 9x6 inches, cloth, $5.00 to SAE nonmembers ($2.50 to members). Contains specifications covering parts and fittings, materials, and small hardware in the automotive field. Also covers standard tests, ratings, and codes.

RELATIVITY THEORY of PROTONS and ELECTRONS. By Sir A. S. Eddington. New York, Macmillan Company; Cambridge (England) University Press, 1936. 336 pages, tables, 11x7 inches, cloth, $5.50. A companion volume to "Mathematical Theory of Relativity." The central problem is concerned with the conditions which fix the amount of mass and electric charge carried by protons and electrons.

PASCAL, the Life of Genius. By M. Bishop. New York, Reynal and Hitchcock, 1936. 398 pages, illustrated, 10x6 inches, cloth, $3.50. Biography of a man whose life had many interests and contacts.

NATIONAL PHYSICAL LABORATORY REPORT for the YEAR 1936. Great Britian, Department of Scientific and Industrial Research. London, His Majesty's Stationery Office, 1937. 144 pages, tables, 10x6 inches, paper. (Obtainable from British Library of Information, 270 Madison Avenue, New York, $0.80.) Contains a résumé of the research work done in 1936 in the departments of physics, electricity, radio, and engineering.

MOTOR and CONTROL APPLICATIONS. By G. H. Hall. New York, McGraw-Hill Book Company, 1937. 259 pages, illustrated, charts, tables, 9x6 inches, cloth, $3.00. Contains information for the machine designer; also presents data and dimensions of motors as standardized by the National Electrical Manufacturers Association.

MARCONI, the Man and His Wireless. By O. E. Dunlap, Jr. New York, Macmillan Company, 1937. 360 pages, illustrated, 9x6 inches, cloth, $3.50. A "biography" of wireless telegraphy, from infancy to maturity, combined with personal information concerning Marconi.

FUNDAMENTALS of VACUUM TUBES. By A. V. Eastman. New York and London, McGraw-Hill Book Company, 1937. 438 pages, illustrated, 9x6 inches,, cloth, $4.00. Discusses the basic theory underlying the operation of all types of modern vacuum tubes. Discusses at length high-vacuum tubes, mercury-vapor tubes, and several special varieties, with engineering analyses of their more important applications.

ELECTRIC POWER DEVELOPMENT in the U.S.S.R., edited by U.S.S.R. Committee for International Scientific and Technical Conferences, Krzizhanovsky Power Institute of the Academy of Sciences of the U.S.S.R. London, Lawrence and Wishart, Ltd., 1936. 496 pages, illustrated, 9x6 inches, cloth, $3.00. An exposition of the principal technical and economic problems of electrical development in the Soviet Union, and of the plans for meeting them.

Engineering Societies Library
29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a co-operative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Industrial Notes

New Rod Mills in Operation.—The two parallel continuous rod mills of the American Steel & Wire Co. at Joliet, Ill., have been completed and were formally dedicated on June 23. These mills, designed by the wire company's own engineers, embody all modern improvements and a number of new developments never before used in such mills. Every 40 seconds a No. 5 rod, nearly a mile long, comes off the final pass at a speed of 3428 ft. per minute, as compared with 1500 ft. per minute in the old Joliet mills. Speed practically eliminates temperature drop in the rod during rolling and assures greater accuracy as to contour, and physical properties which improve wire quality. The new project is part of a $5,000,000 development which includes improvements in the South Chicago and Gary billet mills, as well as the wire mills in Illinois. Local power companies supply power at 6600 volts for the new mill. Direct current is supplied by a 4 unit motor-generator set, one generator supplying direct current for general use, the other two generators providing power to the reel motors which must be run in step with the mill at the final pass. One 4500-hp motor drives all the rolls on one mill.

New High Speed Electric Locomotives.—Six new streamlined electric locomotives, more powerful than any of the 53 already in operation between New York and New Haven, have been ordered by the New Haven Railroad and will be built in the General Electric plant at Erie, Pa. Each 3600-hp unit will weigh approximately 130,000 pounds, capable of a speed of over 80 miles an hour. Power will be supplied by six motors on as many driving axles, with each motor having two armatures geared to the one axle.

Cutler-Hammer Appointment.—E. J. Gove has been placed in charge of a new Cutler-Hammer office recently opened in Youngstown, O., at 1106 Central Tower. The new office is a branch of the company's Pittsburgh office.

Ohio Brass Appointment.—E. C. Thompson, formerly supervisor of transmission for the Alabama Power Co., has joined the Ohio Brass Co., Mansfield, O., as sales engineer in the power utilities department. He will spend considerable time in the field contacting utility engineers in connection with transmission problems.

New Resistors.—Electrical resistors of an improved type have been developed by the Ohmite Manufacturing Co., 4835 W. Flournoy St., Chicago. Among the features emphasized are evenness of windings and special vitreous enameled covering.

New Oil Filter Press—A new line of oil filter presses for cleaning and drying insulating oils has been announced by the Westinghouse Elec. & Mfg. Co. These presses are light in weight, have low power consumption and are quiet in operation. Their features include a pump bypass through a 1/4-inch needle valve to test the suction line for leaks; a small tank providing a primary gas trap; a discharge flow taken from the bottom of the filter sections providing a secondary gas trap. Standard outfits are rated 5, 10 and 30 gallons per minute for 60 cycle, 220 volt supply.

New Cable Insulation.—A new synthetic cable compound has been introduced by the General Electric Co. under the trade name of "Flamenol." While similar to rubber in its characteristics, it contains no rubber and will not support combustion. It is also highly resistant to moisture and acids, alkalies and oils, and has excellent aging qualities. The properties of the new material are such that it can be made a very soft and flexible compound, or one with celluloid-like rigidity. Flamenol-insulated cable is recommended by the manufacturer for power and control circuits at 600 volts and less, and is well adapted to machine tool wiring, switchboard wiring, and battery and coil leads.

Trade Literature

Lighting Equipment.—Bulletin, 112 pp. Describes lighting equipment for theatrical, architectural, photographic and special purposes. Prices are listed. Century Lighting, Inc., 419 W. 55th St., New York City.

Residential Wiring.—Bulletin, 12 pp. Describes "Durax" non-metallic sheathed cable for residential and similar circuits and interprets its use according to the National Electric Code. Anaconda Wire & Cable Co., 25 Broadway, New York City.

Bus Supports.—Bulletin 34B, 32 pp. Describes outdoor bus supports and fittings. With the parts listed, approximately 50,000 bus support combinations are available. Delta-Star Electric Co., 2400 Block, Fulton St., Chicago, Ill.

Instruments.—Bulletin. Describes instruments for measuring coils, condensers, dielectrics and insulators at radio frequencies; covers the Q-Meter, QX-Checker, the new dielectric unit, the converter test oscillator, Hi-Q parts and inductors. Boonton Radio Corporation, Boonton, N. J.

Motors.—Bulletin. Describes manufacturer's method of integrally-casting end rings, fans and rotor bars of a-c squirrel-cage induction motors, whereby all possibility of bad contacts or loose connections is eliminated, and uniformly high performance is assured. The Reliance Electric & Engg. Co., 1086 Ivanhoe Rd., Cleveland, O.

Detachable Instruments.—Cat. Sec. 43-600, 10 pp. A description of these detachable instruments includes outline dimensions; application data; economic advantages; construction details of the socket and the instrument; accuracy and permanence of calibration; performance characteristics; multiple installations, etc. Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

Insulating Paper Sample.—A novel figure cut from "Manning 300" insulating paper,—a high quality, high density paper for slot insulation and other uses, characterized by extreme toughness, heat aging qualities and extreme dielectric strength. The purpose of the paper character, trade-named "Tuffy," is to illustrate the toughness of the product and unusual resistance to tearing. Insulation Manufacturers Corp., 565 W. Washington Blvd., Chicago, Ill.

Motors.—Bulletin 1032, 8 pp. Describes slip ring motors, 1 to 350 hp., designed for continuous duty, open and enclosed ratings, or for intermittent reversing application, short-time duty rating. Available in open, drip proof, splash proof, fully enclosed and gear head types for horizontal and vertical operation. Century Electric Co., 1806 Pine St., St. Louis, Mo.

Lightning Arresters.—Catalog 390, 116 pp. A comprehensive volume aiming to provide essential data on lightning protection for distribution systems and on Crystal Valve lightning arresters. Much new and up-to-date information has been included in the engineering section. Chapters are devoted to lightning protection for distribution systems, for rural distribution lines, performance characteristics of arresters, and theory of operation of CV lightning arresters and complete descriptions of the various types. Electric Service Supplies Co., 17th and Cambria Sts., Philadelphia, Pa.

Electrical Steel Sheets.—Bulletin, 32 pp. Describes development of electrical steel sheets and modern mill technique in producing this material. Ten grades of USS electrical steel sheets are discussed and many applications are detailed. Conversion tables are included as well as a new table on guaranteed maximum core losses and information on magnet wire and varnished cambric insulated cables made by the American Steel & Wire Co. Terms commonly used, including normal magnetism, hysteresis loss, etc., are treated and explained. The uses of electrical sheets in different types of electrical apparatus are illustrated. United States Steel Corp. Subsidiaries, P. O. Box 176, Pittsburgh, Pa.

Arc Welding Design Chart.—A newly-revised engineering drafting room chart to provide, in concise ready reference form, data necessary for producing arc welded designs. The chart includes the latest weld symbols adopted by the AWS in May. Additional data covers particulars regarding the 16 types of joints for arc welding; illustrated suggestions for better arc welded design; sketches explaining the nomenclature of welds; and a comparison of welded and riveted drawings. Tables are included giving properties of base metals, weld metals, electrode metals, etc. The Lincoln Electric Co., Cleveland, Ohio.